ILLINOIS STATE WATER SURVEY

at the

University of Illinois
Urbana, Illinois

EVALUATION OF POTENTIAL BENEFITS OF WEATHER MODIFICATION ON AGRICULTURE

by

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FINAL REPORT - PART I

DESCRIPTION OF INDIVIDUAL STUDIES

Contract 14-06-D-6843

Sponsored by

U.S. Department of Interior
Bureau of Reclamation
Office of Atmospheric Water Resources

October 31, 1971

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ACKNOWLEDGMENTS

Major assistance in economic aspects of the research was provided by Dr. Earl Swanson, Professor of Agricultural Economics, University of Illinois. Dr. Paul T. Schickedanz was instrumental in development of the regional prediction equations and provided assistance on various statistical problems. Mr. Thomas Henderson, Atmospherics Incorporated, was helpful in assessing seeding costs and advising on other operational considerations.

Elmer Schlessman was responsible for much of the data analysis and supervision of subprofessional personnel. Marvin Clevenger supervised the machine processing involved in the project. John Brother provided valuable assistance in the drafting of illustrations for technical papers and this final report. Linda Schmidt and Brenda Rattner, student assistants, accomplished much of the large amount of routine data analysis required in accomplishment of the research.

KEY WORDS AND DESCRIPTORS

1. Weather Modification
2. Summer Rainfall
3. Climatology
4. Agriculture
5. Corn and Soybean Yields
6. Natural Weather Effects on Crop Yields
7. Technology Effects on Crop Yields
8. Cloud Seeding Effects on Crop Yields
9. Economic Analyses of Seeding Effects on Crop Yields

ABSTRACT

An investigation was made of the potential effects of modifying growing-season rainfall on the yields and economic benefits of the two major Illinois crops, corn and soybeans. Crop yield and weather data for the 38-year period, 1931-1968, were used to develop multiple regression equations relating crop yield to technology trends and various temperature and precipitation parameters. This was done for each of 13 regions with similar yield characteristics. Hypothetical seeding models were then used with the appropriate regional equation to evaluate the effects of seeding-induced changes in July-August rainfall on crop yields. Frequency distributions were developed to define expected gains or losses from seeding with each hypothetical model under assumed seeding operations lasting 1, 2, 3, and 5 years. Results indicated that in most regions of Illinois, corn and soybean crops would be benefited in the majority of the growing seasons through a cloud seeding program. Reaction to the potential seeding was found to vary substantially between regions with the same seeding model because of differences in soil properties and, to a lesser extent, climatic variations. Furthermore, seeding effectiveness may vary considerably from year-to-year with the same model in the same region due to the temporal variability in daily rainfall distribution characteristics.

INTRODUCTION

Purpose and Scope of Research

The research discussed in this final report was undertaken to provide quantitative estimates of the potential effects of cloud seeding on crop production. Previously, pilot studies at the Illinois State Water Survey had demonstrated the feasibility of providing the answers for a representative midwestern state (Illinois) and for deriving the necessary analytical techniques for extension of the evaluation to the Great Plains and other regions. In this study under Contract 14-06-D-6843, evaluation of agricultural potential benefits were confined to the two major Illinois crops, corn and soybeans.

Three basic tasks were undertaken. These included 1) determination of weather-yield relationships for corn and soybeans in Illinois with division of the state into regions of equivalent yield characteristics, 2) development of methods to evaluate quantitatively the effect of seeding-induced rainfall changes on yields of these crops, and 3) preliminary assessment of the economic value of yield increases resulting from cloud seeding.

An important consideration in the development of the methodology for assessing increased crop yields (benefits) from rainfall augmentation in Illinois was to establish methods applicable to all areas of the United States. If the methods developed here were found to be useful and reliable, then further subsequent studies would be desirable. These would include a careful assessment of the economic benefits, evaluation in other states for other major crops, and evaluation of future benefits taking into consideration advances in agricultural technology.

Data Used in Research

Weather and crop yield data for corn and soybeans in the 102 counties of Illinois during the 38-year period, 1931-1968, were used in the research. In the 102 counties, satisfactory weather data on temperature and precipitation were available for use from 60 stations of the National Weather Service (formerly U.S. Weather Bureau) during the 38-year sampling period (Fig. 1). Monthly mean temperatures, monthly rainfall, and daily rainfall amounts were the weather parameters used in various aspects of the investigation. County crop yield data for each year were obtained from annual summaries of Illinois agricultural statistics, published by the Cooperative Crop Reporting Service, Illinois Department of Agriculture.

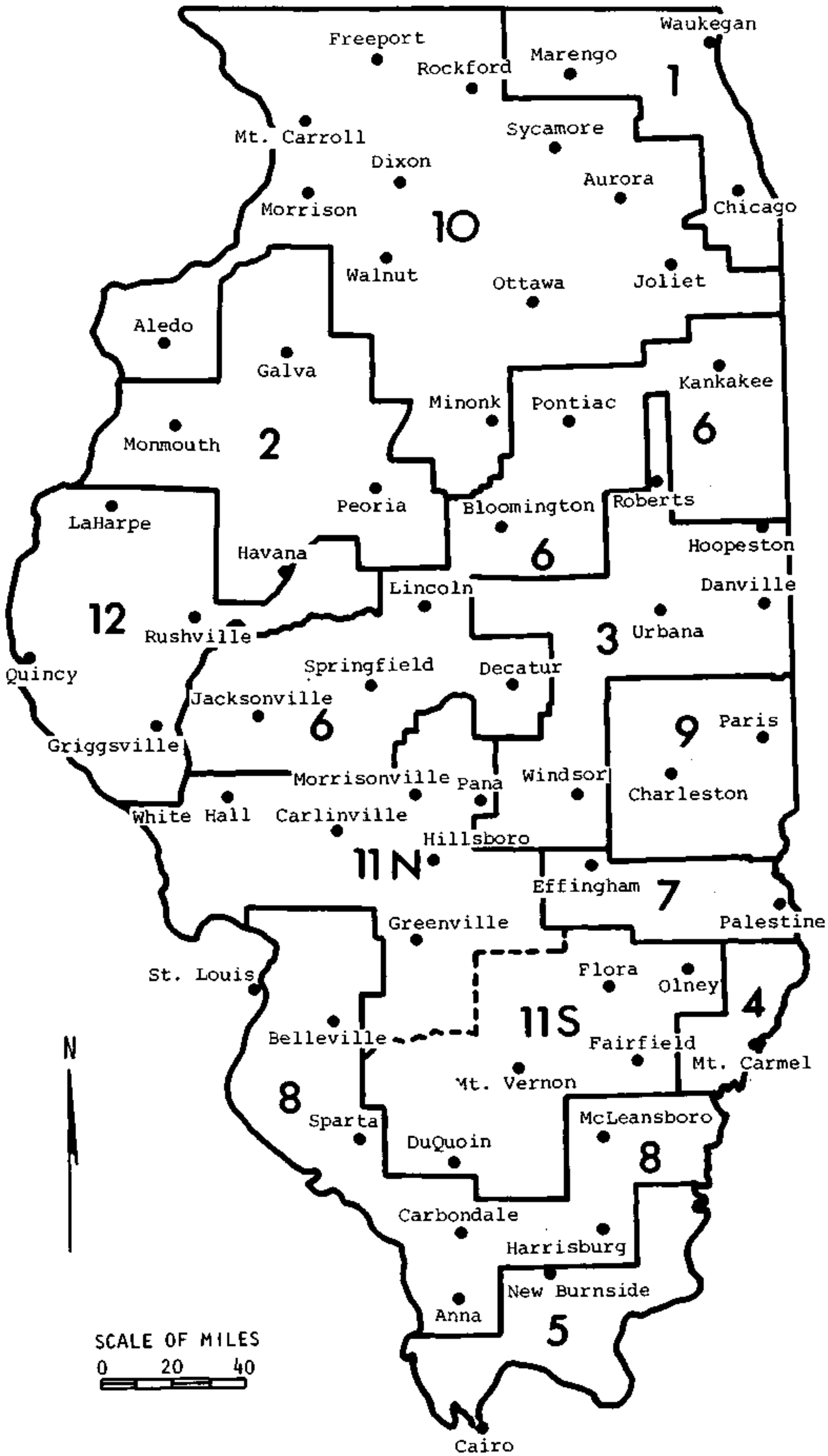


Figure 1. Weather-crop yield regions and climatic stations

ANALYTICAL TECHNIQUES AND METHODS

Basic Initial Decisions

In the early stages of the research, a number of basic decisions were made which guided the analytical tehcniques and methods later employed in various studies. The more important of these decisions are listed below.

1. Evaluation of seeding effects would be based strictly upon hypothetical seeding-induced changes in July and August rainfall. These are the two months which earlier studies by Changnon (1966) showed to be most important in affecting yields. Yields were found to be relatively insensitive to other precipitation parameters.

2. No predictive capability for July-August rainfall amounts would be assumed, except for that provided by statistical probabilities derived from climatic data. That is, it was assumed that no long-range weather forecasting capability of sufficient accuracy to be used in planning seeding operations was available.

3. The temperature would not be varied in the regional prediction equations in calculating seeding effects. The observed temperature for each month was used and it was assumed that seeding operations do not alter temperatures sufficientily to change crop yields significantly.

4. For the purposes of our investigation, it would be assumed that no undesirable downwind effects occur from seeding carried out in the target region.

5. The sampling period selected was 1931-1968 for which suitable climatic and crop yield data were available.

6. Evaluations of seeding-induced effects would be made for corn and soybeans in all regions of Illinois with distinct soil-water-yield relations.

7. Yields would be calculated for each year of record in each Illinois region through use of existing weather data for that year in the regional prediction equation. For each year, calculations would be made of yields using (1) the observed weather conditions, and (2) selected hypothetical seeding models providing for various degrees of increase (or decrease) from the natural rainfall in July and August.

8. For the year-to-year calculations (1931-1968 period), regional weather models would be developed for each year from historical weather data. These

would consist of constant-change and variable change models. The constant-change were to be obtained by increasing (or decreasing) the natural monthly rainfall in July and August by constant percentages. The median monthly rainfall for the region rainfall stations served as the base for determining the constant change models.

The variable-change models were to be derived from daily rainfall. These would be obtained by ranking the daily rainfall at each regional station for each July and August. Then a median regional model of daily rainfall distribution could be determined from the station rankings and this model used as the basis for the variable-change weather models.

In the variable-change models, it was decided to apply different seeding-induced percentage changes for daily rainfalls in the following groups: 0.10" or less, 0.11" to 0.50", 0.51" to 1.00", and over 1.00". A number of models could then be derived by assigning various percentage changes to these groups. It was tentatively agreed to place an upper cutoff on seeding increases at a daily rainfall of 1.5 inches. That is, it is assumed that the precipitation process is too efficient to be improved under these rainfall conditions.

9. Region 11 (Fig. 1), consisting of 17 counties in south central Illinois, was selected for use in a detailed pilot study to develop further the best techniques and methodology to be used throughout the state. However, because of its large size (approx. 9250 mi^2), and re-evaluation of its weather-crop yield properties, region 11 was divided into two parts, the northern and southern regions. The pilot study was then concentrated in the southern region in which the raingage station distribution is somewhat better than in the northern region.

10. The economic evaluation would be limited to Illinois, although it is recognized that the ramifications of weather modification on agriculture can not be truly isolated to such an area.

11. In calculating seeding costs in the economic evaluations, a fixed fee basis would be used since this is the method presently used by most commercial seeders. That is, they charge a fixed amount per acre for the duration of the seeding contract regardless of the number of seeding operations during the contract period.

12. With regard to application of Illinois findings to other states, it was decided that the methodology should be applicable to major grain crops elsewhere. Therefore, the final report should contain a detailed description of the methodology, including reasons for selection, steps in its development, and how it is used.

Selection of Hypothetical Seeding Models

Two types of hypothetical seeding models were employed in our studies. These were designated constant-change and variable change models. With the constant-change models, yield changes associated with constant seeding-induced increases (or decreases) in all rainstorms were calculated. For example, calculations were made of yield changes resulting from a 25% increase in monthly rainfall during July and August, based upon the assumption that all rains would be increased 25%, on the average, by seeding.

However, it was considered more likely that seeding-induced rainfall varies with rainstorm intensity. Therefore, a series of variable-change models were selected for use in the regional analyses. These are believed to envelop the range of known and potential seeding effects on growing season rainfall. They were formulated on the basic assumption that the percentage increase (or decrease) in rainfall from seeding would be greater when atmospheric conditions produce light rainfall naturally. This assumption is supported by findings from the Whitetop radar analyses (Braham and Flueck, 1970). The hypothetical variable-change models are shown in Table 1.

Calculations resulting from application of the variable-change models in each region were helpful in making selection of the constant-change models (Table 2). Thus, it was found that the average effect of variable-model A combining all regions for the 38-year sampling period was approximately a 25% increase in July - August rainfall. Therefore, for comparison purposes, one of the constant change models was set at 25%. Similarly, other constant-change increase models were designated 12% and 40% to correspond approximately with the net effect of variable models B and E. Constant decreases of 15% and 30% were used to correspond with the range of net effects provided by the decrease models in Table 1.

Table 1. Variable-change models employed to alter various daily rain amounts.

	Variable percentage change for given model						
Daily rainfall (inches)	E_	A_	B_	C	X	Y	Z
0.10 or less	150	100	75	50	-50	-75	-100
0.11 - 0.50	75	50	30	20	-30	-50	-75
0.51 - 1.00	30	20	10	0	-10	-30	-50
Over 1.00	10	0	-10	-20	0	-15	-30

Table 2. Constant-change models for July-August rainfall.

Increases (%)	Decreases (%)
12	15
25	30
40	

Determination of Daily Rainfall Models

For use with the variable-change seeding models, daily rainfall models were derived for each year in each of the regions. For a given region, models were derived for each month used in the hypothetical seeding analyses. Only July and August rainfall were modified hypothetically in the prediction equation, since rainfall in the other months had insignificant correlation with crop yields during the 38-year sampling period (1931-1968). The method used to derive the regional daily rainfall model for a given month in a given year is outlined below.

1. The monthly rainfalls for each stations in the given region were ranked from high to low to determine the regional median.

2. For each station, the percentage of its monthly rainfall resulting from daily amounts in the following class intervals was determined.

    a. over 1.00 inch
    b. 0.51-1.00 inch
    c. 0.11-0.50 inch
    d. 0.10 inch or less

3. From the calculation in number 2 above for each regional station, the average percentage of the regional rainfall in each of the above four class intervals was determined. For example, if there were three stations with 60, 30, and 9%, respectively, of their monthly rainfall occurring in daily amounts over one inch, then the average regional percentage in this class interval would be 33%. The sum of the average regional percentages for all class intervals then add up to 100%.

4. Next, the median monthly rainfall for the region (number 1 above) was multiplied by the average regional percentage for each class interval. This provided the portion of the regional median rainfall to be assigned to each class interval.

5. Then, the regional monthly distributions established in number 4 above were modified through application of the variable-change seeding models described previously. The modified monthly rainfall totals in each year, as obtained with each seeding model, were then inserted in the regional prediction equation to determine the change in yield expected from the additional surface water obtained from the hypothetical seeding.

An example of deriving the regional rainfall model for a given year is provided below through use of data for July 1931 in Region US. Five rainfall stations are included in this region as shown in Fig. 1. Ranked July 1931 rainfall for these stations was 7.71, 5.56, 2.29, 2.20, and 2.04 inches. Median monthly rainfall for the region was then 2.29 inches.

1. From computer printouts, ranked daily amounts for each station were obtained. Thus, at Flora with a monthly total of 5.56 inches, the ranked amounts were 4.15, 0.65, 0.39, 0.29, and 0.08 inches. Therefore, 75% of Flora's rainfall occurred in daily amounts over 1 inch, 12% in daily rains of 0.51 - 1.00 inch, 12% in daily amounts of 0.11-0.50 inch, and only 1% in amounts of 0.10 inch or less.

2. Following the same procedure for the other four stations, and then calculating the 5-station average percentage for each class interval, the following results were obtained:

Daily Amount (in.)	5-Station Average (%)
Over 1.00	45
0.51 - 1.00	33
0.11 - 0.50	20
0.10 or less	2
Total	100

3. Next, the median monthly rainfall of 2.29 inches was multiplied by each of the above class-interval percentages to obtain the portion of the regional monthly rainfall to be assigned to each class interval. This calculation results in the following distribution of the monthly rainfall in Region 11S:

Class Interval (in.)	Monthly Rainfall (in.)
Over 1.00	1.03
0.51 - 1.00	0.75
0.11 - 0.50	0.46
0.10 or less	0.05
Total	2.29

Each variable-change seeding model (described in the previous section) was then applied to the above class-interval distribution to obtain the seeding-modified monthly total for July 1931. This calaulation is illustrated for Model A below.

Class Inverval (in.)	Monthly Amount (in.)	Model A Multiplier	Seeding-Modified Amount (in.)
Over 1.00	1.03	1.0	. 1.03
0.51 - 1.00	0.75	1.2	0.90
0.11 - 0.50	0.46	1.5	0.69
0.10 or less	0.05	2.0	0.10
Total	2.29		2.72

Delineation of Weather-Crop Yield Regions

A necessary initial step in this research study was to determine the regions within the state that had similar crop-yield relations. These "crop-weather regions" should result from the interaction of different soil types within Illinois, the varying climatic differences across the state, and any existing regional technological differences. The effect of added rainfall for potential weather modification would then be studied in each of these delineated crop-weather regions. Thus, the purpose of this particular phase of the study was to delineate objectively such crop-weather regions, using county data on past weather conditions and yields. Yield data for entities smaller than counties were not available; however, the detail furnished in the county mean yields for corn and soybeans in Fig. 2 appears adequate to define regions amenable to seeding.

For each of the 102 Illinois counties, a corn yield-weather multiple regression equation was developed involving the 1931-1963 data 1) on corn yields, 2) on 8 monthly-seasonal weather variables, and 3) on technological factors. The factors from the resulting county equations were to be used in deriving an objective groupings of the counties. The 8 weather factors employed (preseason precipitation, May temperature, June temperature, June rainfall, July temperature, July rainfall, August temperature, August rainfall) were found to explain between 85% and 98% of the corn yield variations in Illinois (Changnon, 1966).

Earlier studies aimed at developing such regional relationships between weather factors and yields in Illinois had been accomplished for all-weather peril insurance research (Changnon, 1966), and in an analytical program aimed at evaluating the potential of irrigation in Illinois (Changnon, 1969). Since the July and August rainfall totals were shown to be the only monthly rains of consequence in determining corn and soybean yields (Changnon and Neill, 1967; Odell, 1959), the developed county equations were used to derive various numerical expressions (for each of the 102 Illinois counties) describing the July-August rainfall relationships with yields.

To determine a value for each Illinois county that would express the July-August rainfall-yield relationships, a basic measure of the yield explaned by these two weather variables had to be calcultated and then made comparable for all counties. It was assumed that yields are dependent on the interactions of July-August rainfall with soil conditions, other weather conditions, technological factors, and certain unmeasured random variation. When county corn (or soybean) yields are compared with July-August rainfall totals using a regression relationship, the variance of the annual county corn yields can be separated into one portion that is explained primarily by July-August rainfall totals and into an unexplained portion that is associated with other weather factors, technology factors, and random variation. The square root of the variance explained by July-August rainfall provides a standard deviation due to this rainfall for each Illinois county. Dividing this standard deviation by the county mean corn yield and multiplying by 100 resulted in an estimate of the standard deviation of county corn yield. This desired expression of yield relationship with July-August rainfall was termed the "index of variation".

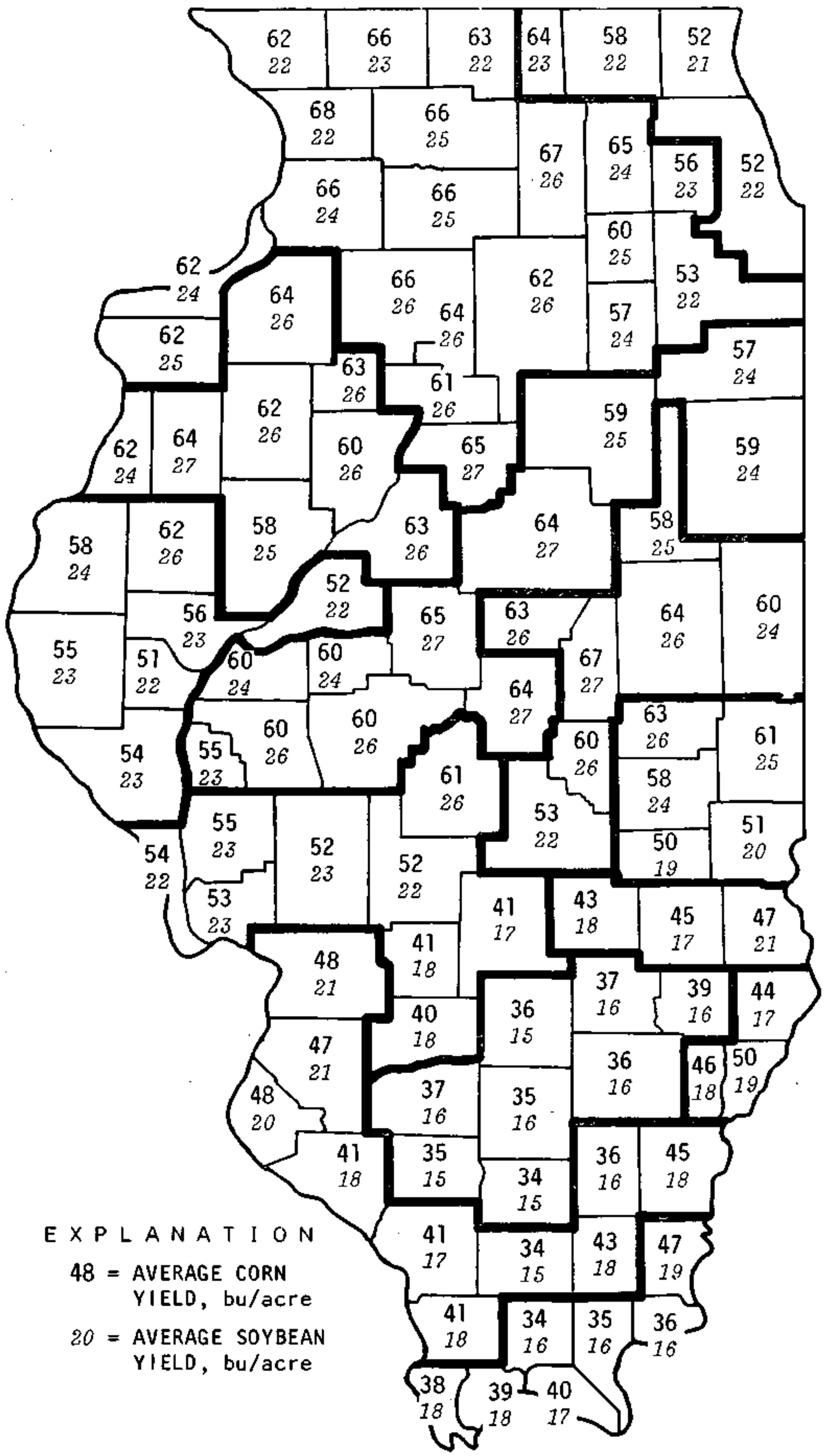


Figure 2. Average county yields for corn and soybeans, 1931-1968

These county indices of variation ranged from 8% to 38% of the county mean corn yields. The county indices were plotted on a state base map to develop possible patterns, and this resulted in grouping of counties to form 13 regions within the state. The pattern of these county indices, based on July-August rainfall, was found to be similar to the patterns of 1) the coefficient of variation of corn yields, 2) statewide drought frequencies, 3) extremely high temperatures, and 4) statewide soil types. This substantiated the validity of these indices, the derived pattern, and the 13 regions chosen. Table 3 shows the average and extreme indices for each of the 13 regions delineated in Fig. 1.

Table 3. Average and extreme regional indices of variation for corn, based on county values in each region.

Region	Regional Average, %	Maximum county value, %	Minimum county value, %
1	12	15	8
2	15	20	12
3	21	31	14
4	25	30	22
5	20	26	12
6	23	29	16
7	27	29	25
8	23	29	16
9	24	28	19
10	14	20	8
U N	31	37	23
US	33	38	30
12	24	29	20

Inspection of Table 3 shows that some regions had equal averages (such as Regions 6 and 8 with 23%), but these were identified as separate regions because they were geographically separated by one or more regions (groups of counties) with either higher or lower indices. The average indices for Regions UN and 11S were more than two times greater than those in Regions 1 and 10, indicating that corn yields in these counties in southern Illinois were 2 to 3 times more dependent on July-August rainfall than those in northern Illinois.

A lengthly analysis similar to that described for corn yields was performed on soybean yields and weather factors for the 102 Illinois counties. County regression equations were developed, and the July-August indices of variation were calculated for soybeans. In general, the soybean indices were not as large as those devised for corn (which was not unexpected), but the pattern of soybean indices throughout Illinois was quite similar to that for the corn indices. Therefore, the 13 regions identified for corn were used in the soybean studies.

For each region, the weather data for all weather stations in each region were averaged along with the yields of all counties in each region to develop regional mean weather values and yields for each year in the 1931-68 period. These annual regional values of weather and yields were those used as inputs in the regional regression equations which are described in the following section.

Development of Regional Regression Equations

The weather effect on crop yields varies considerably over the continental United States. In arid regions, the crop yield is almost entirely dependent upon weather, whereas in semi-arid areas it plays a less important but significant role. In the more humid climates in which rainfall is usually sufficient, the interplay is much more difficult to ascertain. Thompson (1966), Changnon and Neill (1967), and Shaw and Durost (1965) have shown that in some years an increase in rainfall will actually reduce the average yield of corn per acre in the corn belt region.

The actual assessment of the weather effect upon crop yield is a very difficult problem. Because it is a difficult problem, various assessment methods have often been met with criticism. Most of the criticism has been involved with how to allow properly for the technology factor/s'. There has been a continuing increase in the average yield of corn per acre during the past 30 years, and it has become quite large in the past 15 years. It is the general concensus that this is largely due to increased technology. The farmer has learned to use more efficient planting rates, appropriate fertilizers, hybrid corn, terracing, contour farming, improved varieties, greater use of chemical pesticides, and improved skills in farming operations". However, as Thompson (1969a) has noted the recent period of rapid increase in yield has also been a period of very favorable corn weather.

Two methods for determining corn yield-weather relationships were considered. The first method will be referred to as the weather index-experimental plot method and the second as the Thompson method. The first step in the weather index-experimental plot method is to construct a weather index for the area of interest (Shaw and Durost, 1965). The weather index is a method of measuring the effects of weather by the use of variation in experimental crop yield data. In this method, the average yield series from certain experimental plots within a crop reporting district of the state are determined. Next, a trend is determined for the experimental crop yield series. This is usually done by one of three techniques. The first technique involves fitting a linear trend to the yield data through the use of regression. The second technique involves the determination of moving averages for the experimental plot data series. Certain adjustments are then made in an attempt to eliminate the effects of extending the period of the moving average beyond the data sample. The third technique involves the use of several linear trends to approximate the appropriate overall trend. In this approach it is necessary to eliminate certain parts of the data, estimate data for gaps in the record, and to use various averages to smooth the series thus obtained. The weather index is computed by dividing the actual crop yield by the trend yield. The weather indices thus obtained are usually weighted and averaged to obtain weather indices for entire states or for the entire corn belt (Shaw and Durost, 1962).

An adjusted crop yield series is then obtained for the crop reporting district or for the state by dividing the actual yield by the weather index. The weather effect for any year is then determined by the subtraction of the adjusted yield estimates from the actual yield. The adjusted series is considered to be the trend due to technology. A second type of weather index, which allows for weather-technology interaction, is sometimes computed by using data from experimental plots in which the technology has been held constant and from experimental plots in which the technology has been allowed to vary over time. With the use of certain adjustments, the second type of weather index can be obtained. However, work by Shaw and Durost (1965) indicate that the ratio between the two types of indices is close to unity.

The Thompson method has varied over the years. Thompson used a multiple regression technique involving various weather variables, technology trends, and crop yield. In his early work (Thompson, 1963), the technology variable was strictly linear, and represented nothing more than the year factor. That is, the years were considered to be technology and were added to the multiple regression as another linear variable. The relationship can be expressed in the form of Equation 1:

$$\text{Crop yield} = A + \sum_{k=1}^{m} B_1 T_k + \sum_{k=1}^{m} \sum_{j=2}^{n} B_j W_{jk} \qquad (1)$$

where:

- A = the intercept of the miltiple regression
- B_1 = the partial regression coefficient for technology (years)
- B_j = the partial regression coefficient for a given weather variable
- T_k = technology (years)
- W_{jk} = a particular weather variable
- n = the number of weather variables
- m = the number of years
- k = a given year

The expected yield is obtained by solving Equation 1 using the values of the weather variables and technology for the various years of record. The technology trend (the yield expected under normal weather conditions) is then obtained by substituting into the equation the average of each weather variable and the value of technology for each year.

For the influence of an individual variable on the crop yield, the corresponding partial regression coefficient and the multiple regression intercept are used. For those terms which do not involve interaction, the other variables are held at average weather conditions. For terms involving interaction, one can calculate yield curves based on various levels of the other variables. The first modification of the Thompson method (Thompson, 1964) involved the use of a trend line based on the rate of adoption of hybrid corn from 1935 to 1945 and the increased rate of fertilizer application (particularly nitrogen) from 1950 to 1963. This trend is determined empirically by splitting the linear trend into various components to allow for the hybrid corn and fertilizer application. In the next modification, Thompson (1966) split the technology trend into two variables. This is primarily an empirical adjustment to allow for the differing rates of fertilizer application and hybrid corn production over the years.

Later, in an effort to eliminate criticism resulting from a small number of degrees of freedom, Thompson (1969a) first computed regression equations for each of five states by using two time trend variables for the technology influence. Next, from the regression equations, the trends expected with normal weather for each state were calculated. The data from all five states were then pooled using yield expected with normal weather in place of the original technology trends. Thus, there is a considerable increase in the number of degrees of freedom. In his most recent modification, Thompson (1969b) has divided the trend into three variables, two linear and one curvilinear. These variables are related to different periods of the historical record and are based primarily upon the use of nitrogen fertilizer.

For the Illinois study, the Thompson method was used instead of the weather index-experimental plot method for the following reasons:

1. Data on experimental plots are not readily available in many parts of Illinois and in other states. Further, the years of records available for existing plots are sparse and intermittent.

2. The desirability of using the moving average technique to isolate the trend is highly questionable.

3. It was considered questionable whether a few isolated plots are truly representative of the soil-weather conditions throughout large areas.

4. For the assessment of the possible benefits of weather modification, one needs a technique that is relatively simple to apply and in which data for the method are readily available. The Thompson method makes use of data which exist and can be obtained easily.

Although the Thompson method was chosen, it was modified somewhat, because it was believed that the technology factor would vary considerably throughout the state. Thus, a technology trend which was developed for the entire state might not be appropriate for the various subareas within the state. Thompson had used an empirical method of developing the technology trend from inspection of fertilizer and hybrid corn data. However, it was found that this type of data was not available for various subareas within the state of Illinois. As indicated in the previous section, regions of specific corn-weather-soil relationships had been determined (Changnon and Neill, 1967) Thus, it was decided to use a technology trend in each region which would be based upon first-, second-, and third-order technology terms in the multiple regression equation for a given area. The choice of whether to use a first-, second-, or third-order term was then dictated by the data and results obtained in each area. The revised technique is described below.

The eight weather variables specified by Changnon and Neill (1967) were used. These included preseason precipitation (September-May), May mean temperature, June mean temperature, July mean temperature, August mean temperature, June precipitation, July precipitation, and August precipitation.

Four squared terms were used and included preseason precipitation, June precipitation, July precipitation, and August precipitation. Three weather interaction terms were used which included June temperature interacted with June precipitation, July temperature interacted with July precipitation, and August temperature interacted with August precipitation. Thus, in the regression equations, there were eight weather variables, but the equation involved 15 weather terms.

The first step in applying the technique to a given region was to determine the multiple regression using the 15 weather terms (as averaged over the area) and the linear technology trend as independent variables, and the yearly average corn yield as the dependent variable. The second step was to determine the multiple regression equation with the same weather terms and linear technology term, but with a second-order technology term added. An F-test was used to determine if there was a significant addition to the sum of squares of the multiple regression when the second-order term was added. If there was an increase in the sum of squares contribution, the new regression equation was then determined using linear, second-order, and third-order terms of the technology variable. Again, the F-test was applied to see if there was an increase in the sum of squares. If there was an increase, a new regression equation was determined using linear, second-, third-, and fourth-order terms of the technology variable. Whenever there was no increase in the sum of squares when the next higher order term of the technology variable was added, the lower order equation was chosen as the appropriate equation. Equations for the various corn regions in Illinois were found to have either second-order or third-order technology terms.

Next, a weather-technology interaction was considered. It was decided to add terms involving cross products between the linear technology variable and certain weather variables to the highest order equation obtained in each region. These terms will be referred to as weather-technology interaction terms. Two methods for determining the interaction terms were used. The first method involved an investigation of the unstandarized regression coefficients for the equations in the various subareas. If the regression coefficients were significant at the 0.05-probability level, the associated weather variable was then included in the regression equation as a cross product between it and the linear technology term. In this method, the number of interaction terms was found to vary within the various corn regions of the state. The second method involved use of the same weather-technology interaction terms for all corn regions. The terms selected were temperature-precipitation interaction in June, July, and August. Multiple regression equations with both types of interaction were determined for all regions of the state. From examination of these results , the second method (constant interaction) was selected for use in all subsequent analyses. The regional equations for soybeans were derived in the same manner described for corn in the preceding paragraphs.

In developing the final form of the prediction equations, a comparison was made of the difference in corn yields obtained with the constant-interaction equations and regional equations in which no interaction was assumed. Results of this study are discussed in the section entitled Supplementary Studies.

As discussed in a later section, final analyses of seeding effects on corn and soybean yields were made by normalizing yields in the 1931-1968 period to a single technology level (1968). This was done to make results more representative of present yields that have improved greatly with advances in agricultural technology.

An example of utilization of the analytical technique described in the foregoing paragraphs is illustrated for Region 11S in Fig. 3. This figure shows that the regional regression equation yields excellent predictions of corn yields for the various years of record. The technology curve in the lower part of Fig. 3 shows the yield due to technology, that is, the yield that would have been expected had the weather been normal. Thus, the deviations of the predicted values from the technology trend line are assumed to be the effects on yields resulting from existing weather conditions. The droughts of the 1930's and 1950's are clearly revealed by the negative departures during these years.

As mentioned previously, predictions with the various hypothetical seeding models were based on use of 1968 technology in the final evaluation. The upper portion of Fig. 3 shows what corn yields would have been during the 1931-1968 period if 1968 technology had been employed. The yield due to technology would have been constant as represented by the horizontal line labeled 1968 technology. As indicated, there would have been less trend in the yields with progressing time than in the lower curves, since all year-to-year variation was assumed to result from weather effects in this analysis. Note that the drought periods are again clearly evident in the yield curve based on 1968 technology.

Regression equation parameters (coefficients and intercepts) for each of the Illinois regions are shown in Tables 70-71 of Part II of this Final Report. Regional averages of the precipitation and temperature variables used in the prediction equations are contained in Table 69 of Part II.

Summarizing, the prediction equation approach was adopted in the Illinois study, because of certain major advantages such as 1) the capability to use historical data on crop yields accumulated for counties, along with rainfall

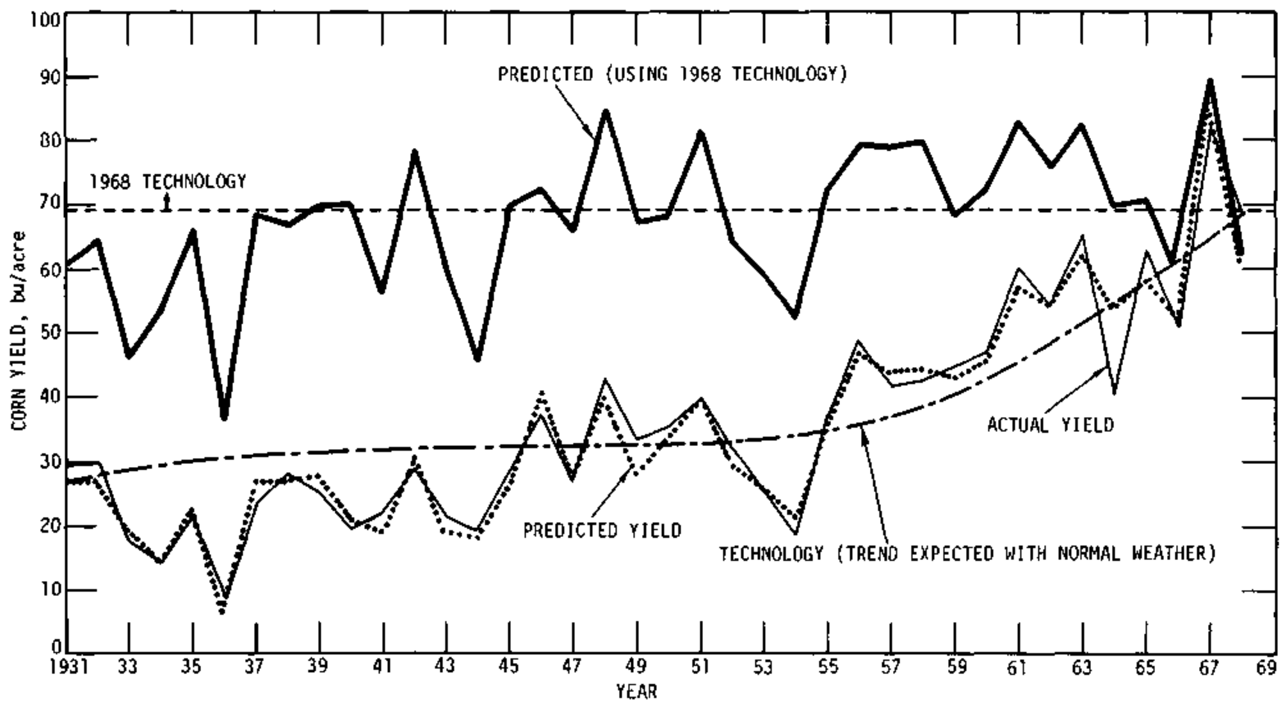


Figure 3. Example of analytical technique used in prediction equation development for Region 11S

and temperature data from numerous long-term cooperative weather stations of the National Weather Service, 2) the opportunity to test crop response under actual farm conditions, 3) the simplicity of the technique which provides an approximate profile of crop response, and 4) the suitability of the technique for application in other areas of the United States. However, certain disadvantages must be recognized also. These include 1) the possibility that the data (yields and weather) may not be from geographic units having uniform production conditions and which conform to optimum sizes of seeding units, 2) the historical weather data may not include all types of weather conditions relevant for weather modification, and 3) specific technology-weather interactions cannot be identified. Overall, however, the method is believed to be the most suitable available at this time for the task undertaken in the Illinois research.

Economic Considerations

Large-scale weather modification provides a good example of what economists refer to as externalities, both pecuniary and technical. When the actions of a business or a consumer, or groups of businesses or consumers, are such that prices or costs are affected for other businesses or consumers, a pecuniary externality exists. Cloud seeding undertaken by a large group of farmers may cause crop production to increase to the point that it would have a price-depressing effect. Increases in yields may also cause corn storage rates to increase, hog production to increase, etc. All of these possible effects of large-scale weather modification have the common element that they occur via the market; changes in supply and demand conditions are reflected in adjustments of prices and costs until a new equilibirum is reached.

The second type of externality occurs when the action of a firm or consumer causes an unintended benefit or cost (damage) to another firm or consumer. This "spill-over" may occur, for example, because of lack of control over the process. Large-scale weather modification intended primarily for agricultural production may affect others either beneficially or harmfully.

In the Illinois project both types of externalities (pecuniary and technical) are assumed to be of minor significance. If corn production were increased by weather modification that costs less than the value of yield increases, costs per bushel would decrease. If corn production in the entire state of Illinois increased by, say, 5 percent, there would be a short-run depressing effect on corn price. Since about 20 percent of the U.S. corn supply is produced in Illinois, this change in output would affect price. Even after an adjustment to this short-run lower price had been worked out on both the supply and demand side to a somewhat higher price, but still lower than before effective weather modification, we would find that food costs to consumers would be lower than before effective weather modification because of the more efficient production.

Our evaluation in this project focuses on the initial step in the process— given the prevailing crop prices in the period 1965-69, what are the expected benefits of weather modification? If the net benefits are sufficiently high, the practice will be adopted by individual farmers or groups of farmers without consideration of the aggregate effects of widespread adoption of weather modification. It is not likely that any single group organized for cloud seeding would be sufficiently large to affect the crop prices with the increased production.. There is reason to believe that, if shown to be profitable, the introduction of weather modification would follow the general pattern of other techniques which farmers have adopted without regard to the final effects on prices and incomes. The innovators and early adopters are the ones who capture the profits from new technology. Those farmers who are the last to adopt new practices are forced to do so to remain in business. Thus, in this study we attempt to answer the question of the magnitude of the profit incentive that would start the adoption process. We do not study the ultimate ramifications except to note that, if profitable, food costs would be lowered by weather modification.

Possible technical externalities are also not taken into account in this study. Such beneficial side-effects of cloud-seeding as those which increase water supply in reservoirs are neglected. There may also be some damage inflicted on non-farm residents by augmented rainfall.

Corn and soybeans are assumed to be the primary beneficiaries of cloud seeding in July and August. Other crops might also be considered. In particular, hay and pasture crops may also be improved by augmented precipitation during this period. Initial analyses indicated that because of the difficulty of measuring changes in production of these crops, they would need to be omitted from consideration. Thus, it is believed that the technical externalities not taken into account are not very important and where they do exist, they are in the nature of benefits. This means that the estimated returns may be underestimated as compared to a more comprehensive analysis.

RESULTS OF PRIMARY STUDIES

Effect of Variable-Change Seeding Models on Rainfall Distribution

Once the variable-change models had been defined in terms of daily rainfall modification, the next logical step was to ascertain the net increase in available water resulting from application of the various models. This was done on a monthly basis by deriving frequency distributions of the percentage change in July and August rainfall totals resulting from applying the various models to the actual daily rainfall data from each region in each of the 38 sampling years (1931-1968). These frequency distributions then provide a measure of the effectiveness of the various increase models in augmenting summer rainfall and of the decrease models in moderating the rainfall in overly wet years.

Detailed results of the above analyses are tabulated in Tables 1 to 7 in Part II (Appendix) of this report. However, the general nature of the results is illustrated in Table 4 which shows the average effect of each variable-change model on monthly rainfall in the July-August period. Average percent of the naturally-occurring rainfall is shown for each model and each region, based upon use of all months in the 1931-1938 period. Then, the data are grouped according to months in which the natural rainfall was above and below normal, and computations made for the appropriate models in each group. That is, average values are shown for increase models in below-normal months and for decrease models in above-normal months. Model C is included in both groups because it operates almost equally as an increase and decrease model.

Table 4. Average effect of variable - change models on July-August rainfall distributions

Seeding Model	Percent of natural monthly rainfall for given region													
	1	2	3	4	J5	5	7	8	9	10	11N	11S	12	Median
						All months combined								
E	144	143	141	142	141	142	141	141	138	139	141	141	140	141
A	128	127	125	125	124	126	124	125	123	124	125	126	124	126
B	114	114	112	111	111	112	111	112	110	110	112	112	110	112
C	10 3	10 3	101	100	100	101	100	101	100	100	102	101	100	101
X	85	85	86	86	87	86	86	86	87	87	86	86	86	86
Y	66	67	68	68	68	67	68	68	69	69	67	67	68	68
Z	46	46	48	49	48	47	48	48	50	49	47	47	48	48
						Below normal months								
E	157	153	151	153	150	147	148	147	146	144	147	148	149	148
A	137	134	133	135	132	129	131	130	128	127	129	129	131	131
B	122	119	118	119	116	115	116	115	114	114	115	116	116	116
C	111	108	107	108	106	104	106	104 "	104	103	104	104	104	104
						Above normal months								
C	97	98	98	95	94	100	96	98	97	98	94	95	95	97
X	88	90	88	91	91	87	90	89	90	88	92	90	91	90
Y	71	72	70	73	73	69	72	70	72	70	74	72	73	72
Z	52	54	51	54	55	49	53	51	54	51	57	53	54	53

In Table 4, Model A, with an average increase ranging from 2 3% to 28% and a median of 26% for all months combined, agrees quite well with seeding results claimed in the past by some commercial seeders. Model C with its median of +1% among the 13 regions and fluctuations between increases and decreases (see tables in Appendix) would satisfy the past attitude of certain cloud physicists better. Model C would also be more realistic of the net seeding effects expected in the Illinois region with continuous seeding, based upon latest findings from the Missouri Whitetop data (Braham and Flueck, 1970); that is, seeding may increase or decrease the summer rainfall depending upon existing atmospheric conditions of moisture and stability.

When the increase models are applied to below-normal months only, their effectiveness increases somewhat as indicated by the change in median values in Table 4. Percentagewise, the decrease models are somewhat less effective in above-normal months than in all months combined; however, the actual decrease in inches of water would be more in much above-normal months than in a near-normal month.

The effect of the various models on monthly rainfall distributions is illustrated further in Fig. 4. This figure shows frequency distribution curves for Region US derived from July daily rainfall data during the 38-year sampling period. For each model, considerable time variation exists in the net effect upon monthly rainfall. For example, the median value (50%) for Model E, is 144% of the regional median rainfall, or a seeding induced increase of 44%. However, Fig. 4 indicates that in a given year selected at random there is a 5% probability that the seeding-induced increase in July total rainfall will equal or exceed 62% of the natural monthly rainfall in Region US. A similar probability exists that the seeding-induced increase will be 28% or less. This range in the net effect of Model E results from year-to-year variability in the natural distribution of daily rainfall.

The time variability in the effectiveness of rain augmentation with a given model, as illustrated in Fig. 4, indicates that seeding success may vary substantially between years with application of the same seeding method. In turn, this provides a partial explanation for the controversial results obtained in past cloud seeding experiments and commercial operations, and, at the same time, vividly portrays one of the obstructions in the path of statistical verification of cloud seeding effectiveness.

Seeding Effects on Corn Yields

Seeding effects were determined through derivation of frequency distributions of corn yield gains or losses in each region when various hypothetical seeding models were applied. Frequency distributions were derived for assumed seeding periods of 1, 2, 3, and 5 consecutive years. This

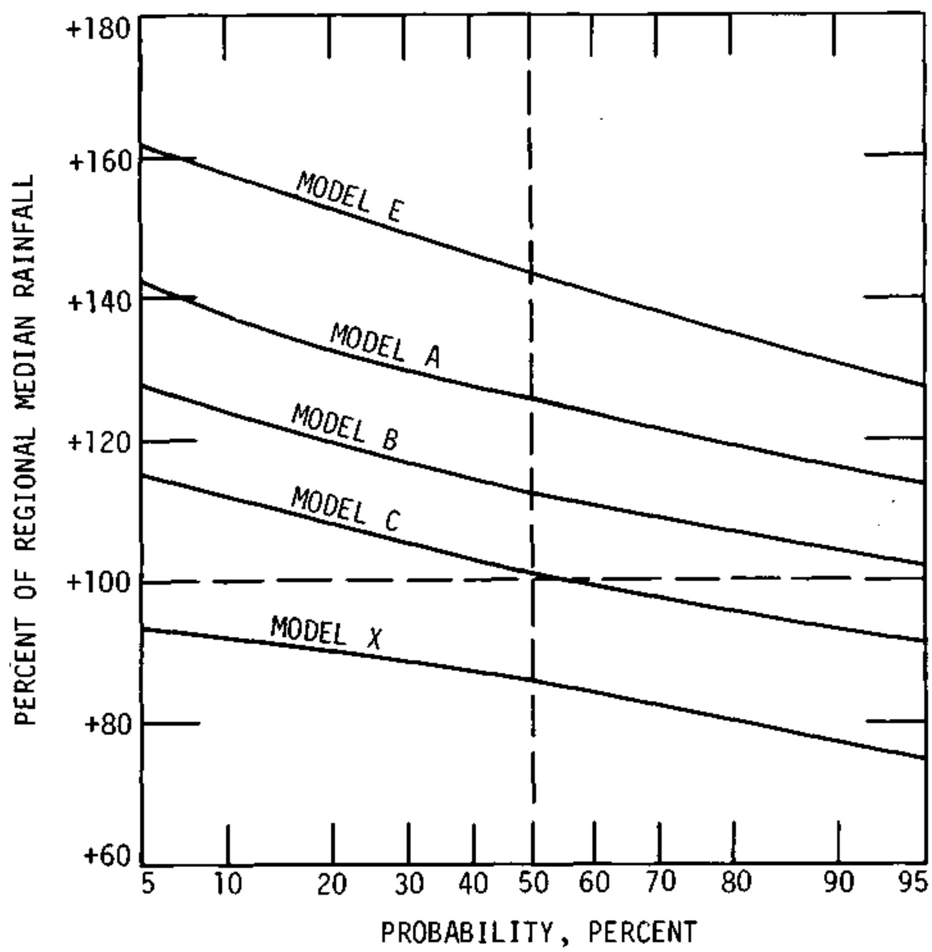


Figure 4. Effect of applying variable-change models to July rainfall in Region 11S

was done to provide information on the magnitude of benefits (or disbenefits) with increasing length of seeding operations.

The above frequency distributions were derived in the following manner from the empirically-derived prediction equations.

1. A yield series was calculated for each region with 1968 technology and observed weather during the 1931-1968 period.

2. A second yield series was calculated for each region using each hypothetical seeding model.

3. The estimated gain (loss) in yield was found by subtracting 1 from 2. These differences were then used to construct the frequency distributions.

Analyses of regional corn yields with the derived prediction equations indicated that seeding effectiveness increases with improvements in technology due to the interaction between technology and weather factors. This problem was overcome by normalizing yields in the long-term observational period (1931-1968) to a single technology level, that existing in the latest year in the sampling period (1968). Use of the 1968 technology level makes analytical results more representative of present seeding potential. Furthermore, Berry (1970) has shown that the percent of corn acreage fertilized in Illinois is approaching its maximum, and the rates of application are increasing but at a decreasing rate. Both conditions suggest that Illinois farmers are approaching or have approached the economic maximum amount of fertilizer on corn. The use of 1968 technology merely involved recalculation of the 1331-1968 yields with the appropriate prediction equation, using the 1968 level for each year rather than the technology level that actually existed in each year.

The variable-change models (Table 1) were applied first to the 1931-1968 data in each of the 13 regions to evaluate potential benefits to corn yields. Table 5 shows calculated yield differences in Region US for several of the variable-change models. These differences were computed for each region and each model and formed the basis for the derived frequency distributions of yield changes.

Fig. 5 illustrates the differential effect of seeding operations conducted over periods of 1 to 5 years in duration. Probability curves are shown for corn yield changes (bu/acre) for Model A in Region US. The 2-, 3-, and 5-year curves were constructed from moving averages of yield changes in the 38-year sampling period. As expected, the possibility of a major benefit is greater in a single-year operation (selected at random), but the possibility of a disbenefit (yield loss) is also greater with short-period operations. In this particular case, the probability of a yield gain is 73% with a single-year operation and 96% with a 5-year randomized operation.

Table 5. Corn yield differences (bu/acre) for given seeding model in Region US.

Year	E	A	B	C	X	Y	Z	Rain (inches)	Departure from normal
1931	+1.4	-2.2	-4.2	-7.1	-8.2	-11.0	-13.4	7.88	+1.41
32	+7.0	+3.6	+0.4	-1.8	-3.9	-7.3	-10.2	8.24	+1.77
33	+0.7	-0.4	-1.5	-2.4	-1.7	-3.2	-4.9	5.08	-1.39
34	+0.2	+0.1	-0.1	-0.5	-0.5	-1.6	-3.2	8.39	+1.92
35	+2.5	+1.1	-0.1	-1.1	-2.8	-4.5	-6.4	4.59	-1.88
36	+3.2	+2.4	+1.8	+1.2	-0.5	-1.6	-3.0	2.46	-4.01
37	+6.7	+5.0	+3.4	+2.0	-0.2	-3.0	-6.5	5.10	-1.37
38	+1.5	+1.5	+1.0	+0.3	-0.4	-2.5	-5.6	8.73	+2.26
39	+6.4	+3.1	+2.1	+0.8	-2.1	-4.6	-7.2	6.69	+0.22
1940	+0.5	-0.6	-1.5	-1.9	-3.3	-3.9	-4.8	2.92	-3.55
41	+5.1	+3.9	+2.7	+1.8	-0.9	-3.0	-5.7	4.73	-1.74
42	+2.3	+1.3	+0.3	-0.7	-1.0	-2.9	-5.3	6.88	+0.41
43	+2.4	+1.3	+0.4	-0.4	-1.2	-2.6	-4.5	2.31	-4.16
44	+7.0	+3.9	+1.4	-0.1	-2.8	-5.2	-7.7	6.56	+0.09
45	+2.9	+0.7	-1.0	-2.3	-4.7	-6.4	-8.9	5.76	-0.71
46	+1.5	-3.1	-6.6	-9.1	-11.4	-15.1	-18.8	9.03	+2.56
47	+7.4	+4.5	+1.9	-0.3	-0.9	-5.4	-9.3	6.61	+0.14
48	-3.9	-1.7	-0.5	-0.2	+0.7	+0.3	-2.1	9.16	+2.69
49	+3.5	+1.8	+0.5	-0.2	-3.4	-4.2	-5.8	4.29	-2.18
1950	+12.6	+7.6	+3.7	+1.0	-2.9	-7.3	-11.2	8.81	+2.34
51	+4.5	+3.2	+1.8	+0.6	-1.7	-4.5	-8.1	6.67	+0.20
52	+3.3	+2.3	+1.1	+0.2	-1.1	-3.2	-5.8	4.52	-1.95
53	+2.0	+1.0	+0.1	-0.8	-1.0	-2.6	-4.3	2.81	-3.66
54	+3.0	+2.1	-0.1	-1.3	-4.0	-5.9	-7.5	6.00	-0.47
55	+0.7	+1.0	+0.7	+0.3	-0.1	-1.9	-4.6	6.22	-0.25
56	+0.2	-1.8	-4.4	-4.6	-6.8	-10.2	-12.9	6.48	+0.01
57	+3.1	+2.2	+1.1	0	-0.7	-3.1	-6.2	7.94	+1.47
58	-12.2	-5.5	-1.1	+1.6	+2.0	+4.2	+3.4	13.88	+7.41
59	+15.3	+8.3	+2.5	-2.0	-2.4	-10.0	-16.8	10.62	+4.15
1960	+5.8	+4.0	+2.4	+1.1	-0.1	-2.6	-5.4	5.10	-1.37
61	+1.4	+1.3	+0.7	-0.1	-0.4	-2.5	-5.6	9.49	+3.02
62	+5.6	+3.9	+2.2	+0.8	+0.2	-2.3	-5.0	7.06	+0.59
63	+1.3	+1.1	+0.5	-0.5	-0.8	-3.2	-6.8	7.16	+0.69
64	+5.0	+3.4	+2.1	+0.9	-1.0	-3.1	-5.5	5.55	-0.92
65	+5.6	+3.4	+1.6	+0.2	-1.4	-3.5	-5.6	6.26	-0.21
66	+3.8	+2.3	+1.2	+0.5	-1.7	-2.6	-3.5	4.70	-1.77
67	+2.3	+0.8	-0.7	-2.0	-4.0	-6.9	-10.4	6.49	+0.02
68	+2.8	+1.3	+0.8	-1.0	-2.8	-4.7	-6.7	4.63	-1.84
No. +	36	31	26	15	3	2	1		
No. -	2	7	12	22	35	36	37		
Mean	+3.3	+1.8	+0.4	-0.7	-2.1	-4.3	-6.9	6.47	

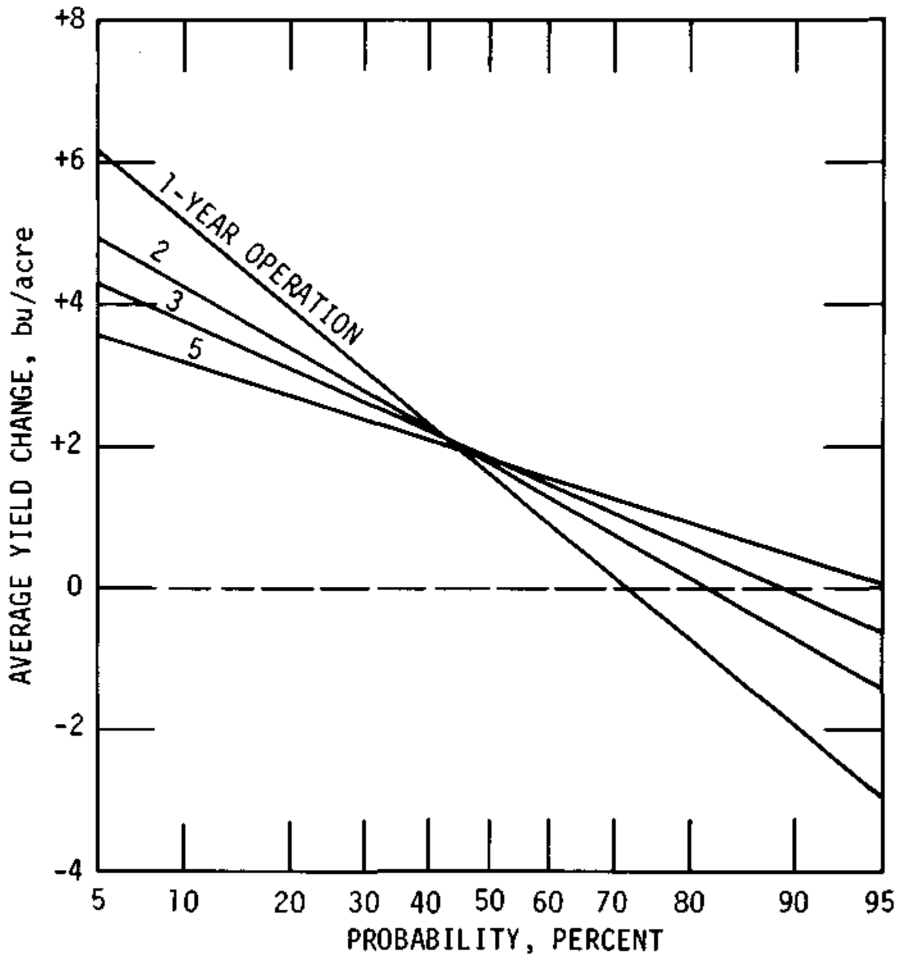


Figure 5. Differential effects of 1- to 5-year seeding operations on average corn yields in Region 11S

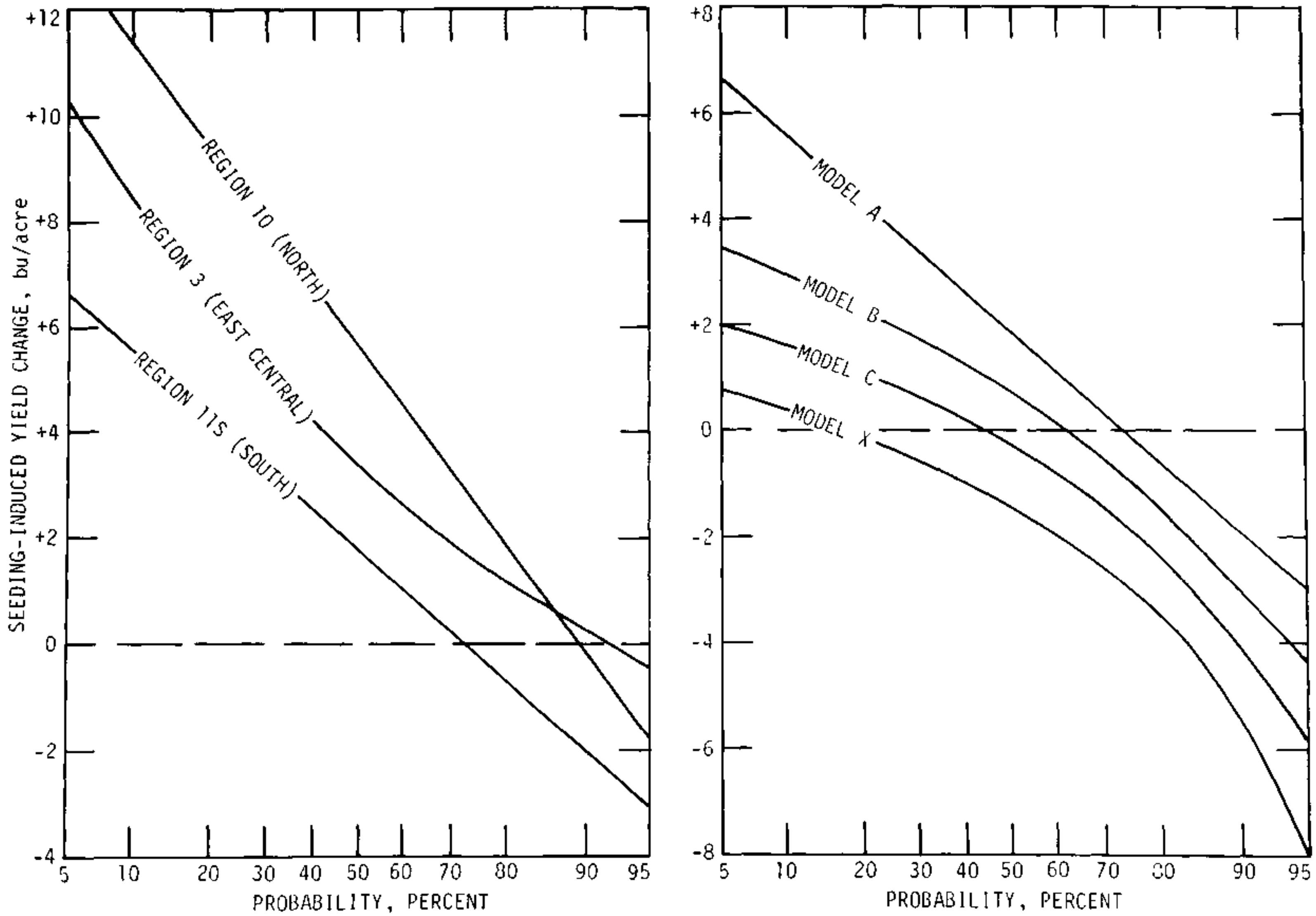
In Fig. 6, the variance in seeding benefits that may occur between regions and between different models in the same region is illustrated. Fig. 6a shows comparative frequency distributions of corn in four regions, based on Model A and a single-year type of operation. As indicated by the intersection of the regional curves with the zero yield-change line, the probability of a yield benefit is 73% for Region 11S, 90% for Region 10 in the northern part of the state, and 92% for Region 3 in east central Illinois. This differential reaction to seeding is related to soil and climatic differences between regions and possibly to differences in utilization of available technological gains.

Fig. 6b illustrates the comparative yield changes with corn obtained from use of several variable-change models based on a single-year operation in Region U S . Model X was intended to be a decrease model. Model C turns out to be a decrease model more frequently than an increase model, whereas A and B are increase models, on the average. From Fig. 6b, it is apparent that the rainfall yield from seeding must be well understood and well controlled under operational conditions to benefit materially corn yields over a substantial period of time in Illinois. Otherwise, there is danger of producing a long-term disbenefit. The danger potential is also related to forecasting capability, and there is need for both seeding control and precipitation forecasting for efficient utilization of weather modification.

Table 6 shows average corn yield differences associated with the variable-change models for each of the 13 regions , along with median values and a weighted state average. This table was computed on the assumption of a continuous year-to-year seeding program. Yield differences have been expressed in both bu/acre and percentage gain or loss to define the seeding effects. Except in Region 5, the increase models (E, A, B) are most effective over the long term. In Region 5,in the extreme southern part of the state only a small percentage of the area is in crops and much of this in the wet soils of the river bottom lands. Thus, in this one region of the state, cloud seeding to augment July-August rainfall would usually be harmful rather than helpful to the corn crop, as indicated by the statistics in Table 6.

In most regions, Model E with its relatively large increases in July-August rainfall is the most effective model. In Regions 7 and 9 where the maximum benefits were obtained from the hypothetical seeding (Table 6), Model E was the most effective model in 35 and 37 years, respectively, during the 38-year sampling period. Table 7 shows the number of years in which each model was the optimum model in each region. From this table, it appears that in most years in the majority of the regions corn yields would be increased by moderate to large increases in the July-August rainfall. In 10 of the 13 regions, the decrease model (X, Y, Z) qualified as the optimum model in 3 years or less during the 38-year sampling period.

Tables 8 to 12 in Part II (Appendix) of this Final Report provide more detailed information on corn yield benefits and disbenefits for seeding operations of 1 to 5 years in duration with the variable-change models. In



a. Regional comparisons of Model A

b. Model comparisons in Region 11S

Figure 6. Comparative frequency distributions of corn yield changes from seeding

Table 6. Average yield differences for corn resulting from continuous application of variable-change models.

	Yield differences (bu/acre) for each given model						
Region	E	A	B	C	X	Y	Z
1	-1.0	+0.8	+1.2	+1.0	-2.3	-5.7	-11.6
2	+2.8	+1.4	+0.2	-0.7	-1.6	-3.1	-4.6
3	+6.2	+3.5	+1.8	+0.5	-0.8	-2.8	-4.9
4	+4.5	+3.8	+2.6	+1.3	-2.4	-6.3	-12.0
5	-2.1	-1.1.	-0.3	+0.3	+0.5	+1.3	+1.8
6	+0.5	+0.5	-0.2	-1.1	-3.6	-6.9	-11.8
7	+11.0	+6.7	+3.0	-0.1	-3.6	-8.9	-14.6
8	+4.8	+2.4	+0.3	-1.4	-3.9	-7.3	-11.0
9	+11.4	+5.9	+1.8	-1.2	-3.1	-6.9	-9.7
10	+9.6	+4.2	+1.7	-2.0	-7.4	-15.8	-26.8
U S	+3.3	+1.8	+0.4	-0.7	-2.1	-4.3	-6.9
U N	+5.9	+3.2	+1.0	-0.8	-2.5	-5.4	-8.3
12	+1.4	+0.3	+0.3	-0.4	-1.5	-3.1	-5.3
Median	+4.5	+2.4	+1.0	-0.7	-2.4	-5.7	-9.7
Average	+5.2	+2.6	+0.9	-0.9.	-3.7	-7.8	-13.1

	Yield difference (%) for each given model						
Region	E	A	B	C	X	Y	Z
1	-1.2	+0.9	+1.4	+1.2	-2.7	-6.8	-13.8
2	+3.1	+1.5	+0.2	-0.8	-1.7	-3.4	-5.0
3	+6.6	+3.7	+1.9	+0.5	-0.9	-3.0	-5.2
4	+6.5	+5.5	+3.7	+1.9	-3.4	-9.0	-17.2
5	-3.5	-1.8	-0.5	+0.5	+0.8	+2.1	+3.0
6	+0.5	+0.5	-0.2	-1.2	-3.9	-7.4	-12.7
7	+14.6	+8.9	+4.0	-0.1	-4.8	-11.9	-19.4
8	+6.8	+3.4	+0.4	-2.0	-5.5	-10.3	-15.5
9	+12.3	+6.4	+1.9	-1.3	-3.3	-7.4	-10.5
10	+10.1	+4.4	+1.8	-2.1	-7.8	-16.7	-28.3
11N	+6.8	+3.7	+1.2	-0.9	-2.9	-6.3	-9.6
11S	+4.9	+2.7	+0.6	-1.0	-3.1	-6.4	-10.3
12	+1.5	+1.0	+0.3	-0.4	-1.6	-3.4	-5.7
Median	+5.2	+2.8	+1.2	-0.8	-2.8	-6.6	-11.2
Average	+5.8	+2.9	+1.0	-1.0	-4.1	-8.7	-14.6

Table 7. Optimum variable-change models for corn and soybeans.

corn

Number of years for each model

Region	E	A	B	C	X	Y	Z	EAB	XYZ
1	17	2	5	3	2	7	2	24	11
2	34	0	0	1	0	1	2	34	3
3	34	1	0	0	0	0	3	35	3
4	30	1	2	4	0	0	1	33	1
5	2	1	1	1	4	2	27	4	33
6	21	3	2	5	5	1	1	26	7
7	35	2	0	0	0	0	1	37	1
8	37	0	0	0	1	0	0	37	1
9	37	0	0	0	0	0	1	37	1
10	36	2	0	0	0	0	0	38	0
11N	37	0	0	0	0	1	0	37	1
11S	35	1	0	0	1	1	0	36	2
12	28	1	2	4	1	0	2	31	3
Median	34	1	0	0	0	0	1		

soybeans

Number of years for each model

Region	E	A	B	C	X	Y	Z	EAB	XYZ
1	30	2	1	1	0	0	4	33	4
2	19	0	0	2	3	5	9	19	17
3	11	6	7	7	4	1	2	24	7
4	32	2	1	3	0	0	0	35	0
5	18	0	0	0	0	0	20	18	20
6	25	6	5	2	0	0	0	36	0
7	34	2	2	0	0	0	0	38	0
8	37	1	0	0	0	0	0	38	0
9	38	0	0	0	0	0	0	38	0
10	30	3	2	2	0	1	0	35	1
11N	37	1	0	0	0	0	0	38	0
11S	36	1	1	0	0	0	0	38	0
12	26	4	3	3	2	0	0	33	2
Median	30	2	1	1	0	0	0		

these tables, the frequency distribution of yield changes of various magnitude are presented for each model and each region. Because the frequency distribution curves for the various operational periods are often non-symetrical and there are round-off and interpolation errors involved in constructing Tables 8 to 12 in Part II, the median values (50%) often differ by small amounts. This also occurs in similar types of tables presented later.

The same analyses performed with the variable-change models were repeated for the constant-change models in six regions (3, 6, 10, 11N, 11S, and 12) selected to represent the natural yield characteristics resulting from various soil conditions and climatic differences within the state. Table 8 shows the average yield changes in both bu/acre and percent associated with the constant-change models. Tables 13 to 17 in the Appendix provide detailed information on the frequency distributions associated with each constant-change model for 1-year to 5-year seeding operations in each of the 6 regions.

Seeding Effects on Soybeans Yields

The analyses performed in the investigation of potential effects of cloud seeding on corn yields were repeated for soybeans. Table 9 is similar to Table 5 and provides a measure of the year-to-year yield changes in soybeans resulting from application of the variable-change seeding models in Region US, with 1968 technology used in the regional prediction equation. Again, computations such as these were made for each seeding model in each region to provide the data for derivation of the frequency distribution of soybeans yield changes.

Fig. 7 is similar to Fig. 5 and illustrates a typical set of soybean frequency curves. Fig. 7 is based upon Model A applied to data for Region US. A substantial decrease in temporal variability occurs between the curves for single-year and 2-year seeding operations, after which only slight changes occur as the seeding effect is averaged over consecutive 3-year and 5-year periods.

Fig. 8 shows a comparison of the seeding effects from application of Model A to corn and soybeans in Region US, in the south central part of the state where soil characteristics and climate are such that seeding could conceivably be a major asset. These curves illustrate a property typical of all models and most regions; that is, the year-to-year cloud seeding effect varies more with corn than with soybean yields. Thus, the probability of a large seeding-induced yield increase is more likely with corn, but a larger decrease may occur also. As shown in this figure, a continuous year-to-year seeding program in Region US with a Model A capability would increase bean yields in 84% of the years and corn yields in 73% of the years.

Table 8. Average yield differences for corn resulting from continuous application of constant-change models.

Region	Yield differences (bu/acre) for each seeding model				
	+40%	+ 25%	+12%	-15%	-30%
3	-0.2	+0.1	-0.3	-3.1	-5.9
6	+6.0	+4.2	+2.6	-0.3	-1.8
10	+10.6	+7.6	+4.1	-6.2	-13.5
11N	+7.6	+4.7	+2.2	-2.6	-5.0
11S	+4.7	+3.0	+1.4	-1.9	-3.9
12	+1.2	+1.0	+0.6	-1.1	-2.4

Region	Yield difference (%) for each seeding model				
	+40%	+25%	+12%	-15%	-30%
3	-0.2	+0.1	-0.3	-3.3	-6.3
6	+6.5	+4.5	+2.8	-0.3	-1.9
10	+11.2	+8.0	+4.3	-2.6	-5.3
11N	+8.8	+5.4	+2.5	-3.0	-5.8
11S	+7.0	+4.5	+2.1	-2.8	-5.8
12	+1.3	+1.1	+0.6	-1.2	-2.6

Table 9. Soybean yield difference (bu/acre) for given seeding model in Region 11S.

	E	A	B	C	X	Y	Z	Rain (inches)	Departure from normal
1931	+1.3	+0.5	-0.4	-1.4	-1.9	-3.9	-6.4	7.88	+1.41
32	+1.4	+0.8	0	-0.7	-1.5	-3.4	-5.9	8.24	+1.77
33	+1.4	+0.6	-0.3	-0.9	-1.7	-2.9	-4.4	5.08	-1.39
34	-1.2	-1.2	-1.4	-1.7	-2.2	-2.8	-3.9	8.39	+1.92
35	+2.7	+1.7	+0.8	+0.1	-1.2	-2.6	-4.2	4.59	-1.88
36	+0.1	+0.1	+0.1	+0.1	-0.3	-0.4	-0.5	2.46	-4.01
37	+2.7	+1.6	+0.7	-0.2	-1.4	-3.1	-5.0	5.10	-1.37
38	-0.4	-0.5	-0.8	-1.1	-1.4	-2.5	-4.0	8.73	+2.26
39	+3.0	+1.9	+0.8	-0.1	-1.3	-3.2	-5.6	6.69	+0.22
1940	+2.5	+1.6	+0.8	+0.2	-1.2	-2.3	-3.7	2.92	-3.55
41	+1.2	+0.7	+0.3	-0.1	-1.1	-2.1	-3.4	4.73	-1.74
42	+2.1	+1.2	+0.3	-0.4	-1.3	-2.8	-4.7	6.88	+0.41
43	-0.2	-0.6	-0.9	-1.1	-1.8	-2.2	-2.7	2.31	-4.16
44	+2.2	+1.3	+0.4	-0.4	-0.9	-2.5	-4.7	6.56	+0.09
45	+0.9	-0.4	-1.7	-2.8	-3.2	-5.1	-7.5	5.76	-0.71
46	+0.2	-0.9	-2.1	-3.4	-3.2	-5.5	-8.5	9.03	+2.56
47	+2.5	+1.6	+0.6	-0.3	-0.5	-2.6	-4.7	6.61	+0.14
48	+1.6	+1.3	+0.9	+0.5	-0.9	-1.9	-3.7	9.16	+2.69
49	+2.7	+1.4	+0.2	-0.7	-2.6	-4.4	-6.6	4.29	-2.18
1950	+3.9	+2.6	+1.2	-0.1	-1.2	-3.9	-7.2	8.81	+2.34
51	+3.1	+1.8	+0.6	-0.4	-2.0	-4.2	-6.9	6.67	+0.20
52	+2.7	+1.8	+1.2	+0.5	-1.3	-2.5	-4.1	4.52	-1.95
53	+2.6	+1.7	+1.1	+0.5	-1.0	-1.9	-2.9	2.81	-3.66
54	+2.1	+1.4	+0.6	0	-1.3	-2.9	-5.0	6.00	-0.47
55	-0.3	-0.4	-0.5	-0.8	-1.2	-1.8	-2.7	6.22	-0.25
56	+2.8	+1.2	-0.6	-1.4	-3.7	-6.2	-9.2	6.48	+0.01
57	+4.1	+3.1	+2.0	+1.1	-1.0	-3.1	-5.8	7.94	+1.47
58	-0.6	+0.2	+0.4	+0.3	-0.8	-2.1	-4.4	13.88	+7.41
59	+1.3	+1.0	+0.5	-0.1	-0.8	-2.0	-4.1	10.62	+4.15
1960	+2.9	+1.5	+0.3	-0.7	-2.6	-4.5	-6.7	5.10	-1.37
61	+3.2	+2.2	+1.2	+0.1	-0.7	-2.8	-5.6	9.49	+3.02
62	+4.6	+3.1	+1.7	+0.6	-1.6	-4.0	-6.9	7.06	+0.59
63	+1.9	+0.7	-0.3	-1.2	-3.1	-5.0	-7.5	7.16	+0.69
64	+4.0	+2.7	+1.6	+0.6	-1.0	-3.1	-5.4	5.55	-0.92
65	+3.7	+2.3	+0.9	-0.4	-1.2	-3.5	-6.3	6.26	-0.21
66	+2.9	+1.6	+0.4	-0.5	-2.2	-4.1	-6.3	4.70	-1.77
67	+5.5	+3.3	+1.4	-0.1	-3.4	-6.4	-10.0	6.49	+0.02
68	+2.1	+0.9	+0.1	-1.0	-1.9	-3.6	-5.5	4.63	-1.84
No. +	33	32	27	11	0	0	0		
No. -	5	6	10	26	38	38	38		
Mean	+2.1	+1.2	+0.3	-0.5	-1.6	-3.3	-5.3	6.47	

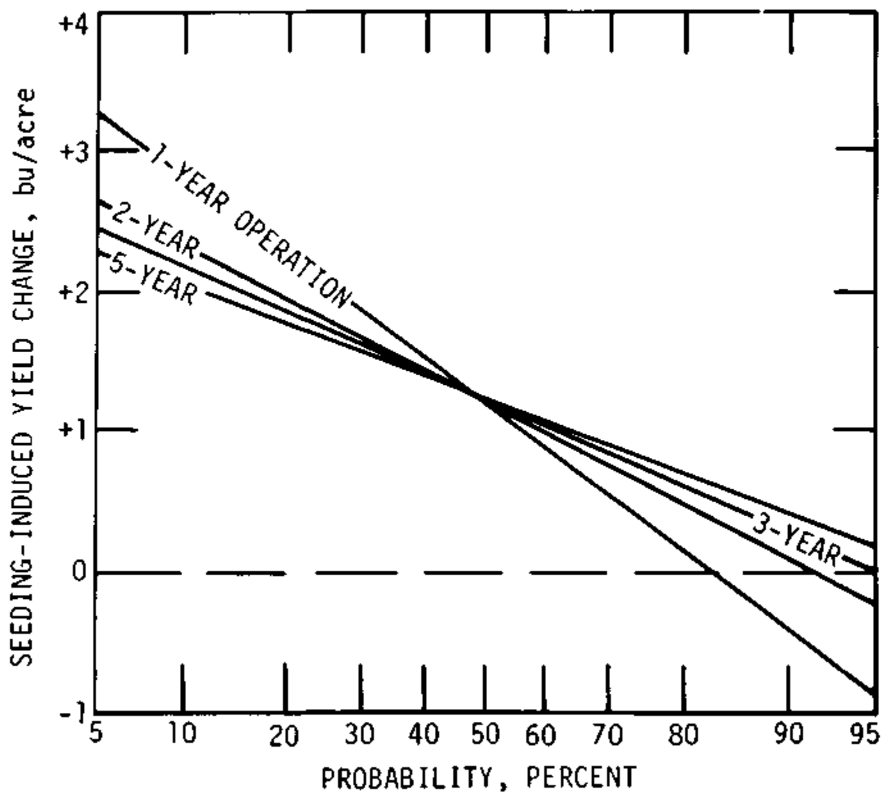


Figure 7. Frequency distributions of soybean yield changes, Model A, Region 11S

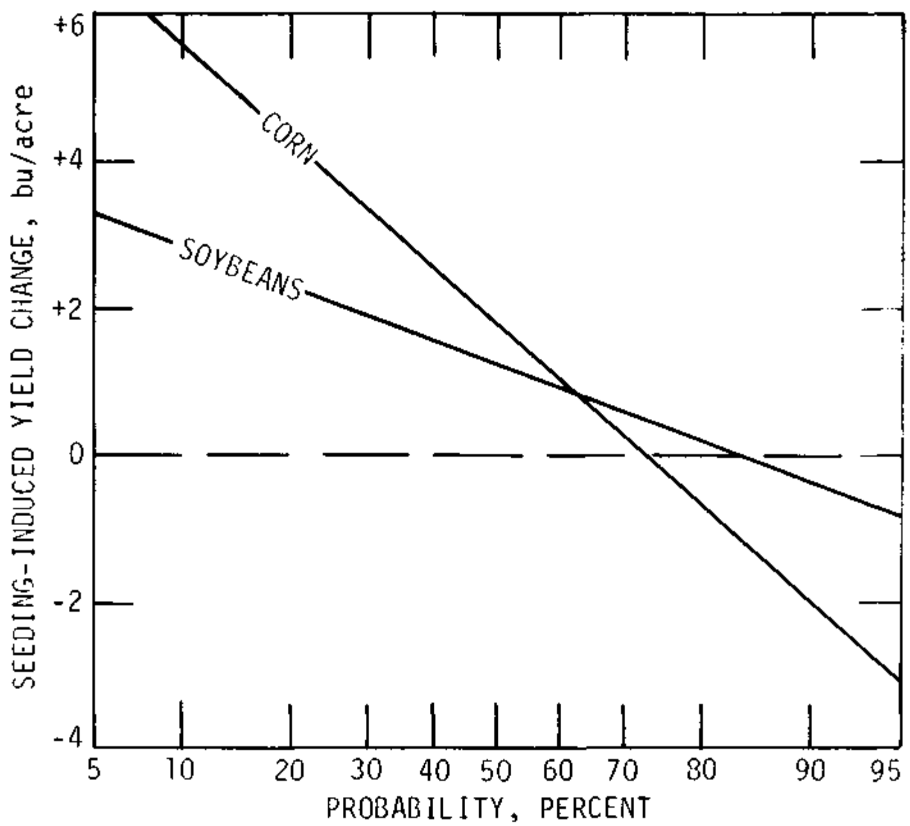


Figure 8. Comparison of corn-soybean frequency distributions, Model A, Region 11S, 1-year operation

Table 10 is similar to Table 6 and shows average differences in soybean yields associated with the variable-change models in each of the 13 regions , along with regional median values and the state average. These tables show that from a percentage standpoint the average yield change for the state is strikingly similar between corn and soybeans with the variabile-change models. Also, from Table 10 it is apparent that the general reaction to application of the various models is similar for both crops. As indicated by the medians, yields are optimized for both corn and beans most frequently with the increase models and Model E is the most frequent optimum among the increase models. More detailed information on the probability of soybean benefits from seeding with the variable-change models is contained in Tables 18 to 22 in the Appendix.

Table 11 shows average yield changes for soybeans using the constant-change seeding models in six representative regions. Tables 23 to 26 in the Appendix provide detailed information on the frequency distributions associated with each of the constant-change models with assumed seeding operations of 1 to 5 years in duration.

Economic Analyses of Seeding Effects

After determining the frequency distributions of seeding-induced changes in corn and soybean yields for the various regions and models, the next problem was how to perform the economic evaluation of the seeding effects. After considerable deliberation on this problem, it was decided to pool the annual benefits (disbenefits) to each crop. From these pooled data, economic frequency distributions were computed in which dollar gains or losses were related to probability of occurrence. These economic frequency distributions were based upon use of average corn and soybean prices in the 1965-1969 period and their regional acreage distribution in 1967 (see Table 73 in Appendix). Corn and soybean prices used in the calculations were \$1.13 and \$2.56 per bushel, respectively. Specifically, economic benefits were expressed as added income per seeded acre, excluding seeding costs which are relatively small (\$0.05-\$0.15 per acre per year from present estimates).

Fig. 9 illustrates the type of results obtained in the economic analyses. This figure shows the frequency distribution of economic benefits in Region 11S resulting from application of several of the variable-change seeding models. Income differences in dollars per seeded acre have been plotted against probability in percent based upon single-year seeding operations. That is, the probabilities represent values for a crop-growing season selected at random. Frequency distributions similar to those in Fig. 9 were computed for each region, each seeding model, and seeding operations having a duration of 1, 2, 3, and 5 years.

The optimum curve in Fig. 9 represents the income gain assuming the seeder has the capability to select the best variable-change model for use in any given year. As pointed out earlier, Models E and A are definite increase models, Model C is a cross-over model with nearly equal probability of producing gains or losses in a given year selected at random, and Model X is a decrease model which would be used only to suppress rainfall in overly wet years.

Table 10. Average yield differences for soybeans resulting from continuous application of variable-change models.

Region	Yield difference (bu/acre) for each given model						
	E	A	B	C	X	Y	Z
1	+1.9	+1.2	+0.5	+0.1	-0.7	-1.6	-2.5
2	-1.3	-1.2	-1.1	+1.0	-1.3	-1.3	-1.4
3	-0.5	0	+0.1	+0.1	-0.3	-1.0	-2.1
4	+2.0	+1.4	+0.9	+0.3	-0.7	-2.0	-3.7
5	+0.3	+0.1	0	0	+0.1	+0.2	+0.5
6	+1.1	+0.9	+0.3	-0.3	-1.8	-3.7	-6.4
7	+2.2	+1.5	+0.8	+0.1	-1.0	-2.6	-4.7
8	+2.1	+1.1	+0.2	-0.7	-1.9	-3.6	-5.7
9	+3.7	+2.1	+0.8	-0.2	-1.3	-2.9	-4.7
10	+1.1	+0.7	+0.3	-0.2	-1.0	-2.2	-3.9
US	+2.1	+1.2	+0.3	-0.5	-1.6	-3.3	-5.3
UN	+1.9	+1.2	+0.4	-0.3	-1.2	-2.5	-4.2
12	+0.6	+0.4	+0.2	-0.1	-0.6	-1.4	-2.5
Median	+1.9	+1.1	+0.3	-0.1	-1.0	-2.2	-3.9
Average	+1.2	+0.8	+0.3	-0.2	-1.2	-2.5	-4.2

Region	Yield difference (%) for each given model						
	E	A	B	C	X	Y	Z
1	+7.2	+4.6	+1.9	+0.4	-2.7	-6.1	-9.5
2	-4.0	-3.6	-3.3	+3.0	-4.0	-4.0	-4.3
3	-1.6	0	+0.3	+0.3	-1.0	-3.2	-6.8
4	+8.7	+6.1	+3.9	+1.3	-3.1	-8.7	-16.2
5	+1.3	+0.4	0	0	+0.4	+0.8	+2.1
6	+3.5	+2.8	+0.9	-0.9	-5.7	-11.7	-20.3
7	+9.3	+6.4	+3.4	+0.4	-4.2	-11.0	-19.9
8	+8.5	+4.5	+0.8	-2.8	-7.7	-14.6	-23.2
9	+12.4	+7.0	+2.7	-0.7	-4.3	-9.7	-15.7
10	+3.6	+2.3	+1.0	-0.6	-3.2	-7.1	-12.6
UN	+7.0	+4.4	+1.5	-1.1	-4.4	-9.2	-15.5
US	+10.2	+5.9	+1.5	-2.4	-7.8	-16.1	-25.9
12	+2.0	+1.4	+0.7	-0.3	-2.0	-4.7	-8.4
Median	+7.0	+4.1	+1.1	-0.4	-3.7	-8.1	-14.4
Average	+4.2	+2.8	+1.0	-0.7	-4.2	-8.7	-14.7

Table 11. Average yield differences for soybeans resulting from continuous application of constant-change models.

Region	Yield differences (bu/acre) for each seeding model				
	+40%	+25%	+12%	-15%	-30%
3	-0.3	0.0	+0.1	-0.4	-1.0
6	+1.2	+1.2	+0.7	-1.1	-2.7
10	+0.9	+0.7	+0.5	-0.8	-1.8
11N	+2.2	+1.5	+0.7	-1.1	-2.2
U S	+2.3	+1.6	+0.9	-1.2	-2.7
12	+0.2	+0.3	+0.2	-0.4	-1.0

Region	Yield difference (%) for each seeding model				
	+40%	+25%	+12%	-15%	-30%
3	-1.0	0.0	+0.3	-1.3	-3.2
6	+3.8	+3.8	+2.2	-3.5	-8.5
10	+2.9	+2.3	+1.6	-2.6	-5.8
11N	+8.1	+5.5	+2.6	-4.1	-8.1
11S	+11.2	+7.8	+4.4	-5.9	-13.2
	+0.7	+1.0	+0.7	-1.4	-3.4

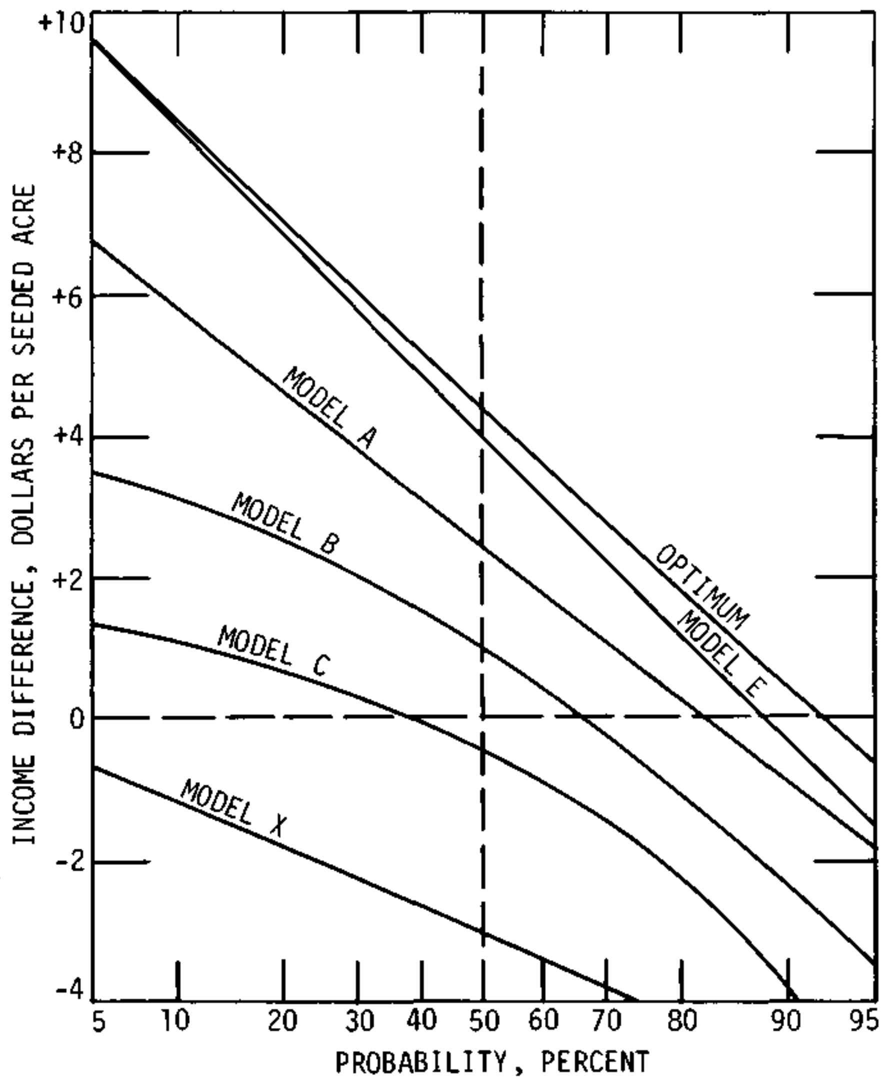


Figure 9. Economic benefits in Region 11S resulting from use of variable-change models

One reason for the year-to-year variability in the efficiency of a given seeding model can be seen by referring back to Fig. 4, in which the frequency distribution of seeding-induced changes in the monthly rainfall for July in Region 11S are shown for the variable-change models of Fig. 9. Using Model A as an example, the median effect of this model is an increase of 26% over the naturally-occurring regional rainfall. However, in a year selected at random there is a 5% probability of a 42% increase in July rainfall and a similar probability of only a 14% increase. This variation is due to the natural temporal variability in the distribution characteristics of daily rainfall upon which the variable-change models operate.

The time variability in the effectiveness of rain augmentation with a given model, as illustrated in Fig. 4, indicates that seeding success may vary substantially between years with application of the same seeding method. In turn, this provides a partial explanation for the controversial results obtained in past cloud seeding experiments and commercial operations, and, at the same time, vividly portrays one of the obstructions in the path of statistical verification of cloud seeding effectiveness.

Table 12 provides an additional measure of the economic benefits that could be derived from application of variable-change seeding models. In this table, a comparison has been shown of the added income per seeded acre with various models, based upon median values for the 13 regions. Therefore, this provides an indication of the statewide benefit that could be attained. For each model, Table 12 shows the added income for selected probability levels. Also, the breakeven point, or the probability of an economic gain in a year selected at random is shown in the table. For example, assuming the entire state was being subjected to a seeding program, Model A indicates a probability of an income increase of $8.6 per acre in 5% of the years on a typical farm, a $2.5 or greater increase in 50% of the years, and a loss of $1.9 or more in 5% of the years (95% level). On the average Illinois farm, application of Model A would achieve an eccnomic gain in 77% of the years.

Table 13 shows a comparison of the economic benefits with selected variable-change and constant-change models in Region 11S. The average effect of Model E on monthly rainfall increase over the 1931-1968 sampling period was similar to the 40% constant-change model; that is, the 38-year average with Model E was approximately a 40% increase in total July-August rainfall. The average effect of Model A was nearly equal to the 25% constant-change model, and Model B was similar to the 12% constant-change model. Overall, the constant-change models were somewhat more effective in augmenting the July-August rainfall than were the equivalent variable-change models. Other analyses indicated that the variable models were somewhat more effective in near-normal years and the constant models considerably better in well below-normal years. This may be due primarily to the basic assumption of little or no seeding effect on heavy rainfall days in the variable models. In below-normal years, augmentation of rainfall on relatively

Table 12. Comparison of added income per seeded acre with various seeding models, based on 13-region medians.

Model	Added income per acre (dollars) equalled or exceeded for given probability (%) 5	10	20	30	50	70	90	95	Breakeven Point (%)
Optimum	12.5	11.0	9.0	7.4	5.4	2.8	0.0	-1.6	92
E	12.4	10.5	8.8	7.1	4.2	2.5	-0.9	-3.2	85
A	8.6	7.4	6.1	4.9	2.5	0.8	-0.9	-1.9	77
B	5.8	4.4	3.8	2.6	1.1	-0.2	-2.6	-3.6	66
C	3.4	2.4	1.6	0.8	-0.4	-1.4	-3.8	-5.1	42
X	1.2	-0.1	-0.9	-1.5	-2.6	-3.8	-5.6	-8.8	10

Table 13. Comparison of added income per seeded acre with various constant and variable-change seeding models in Region US

Model	Added income per acre (dollars) equalled or exceeded for given probability (%) 5	10	20	30	50	70	90	95	Breakeven Point (%)
E	9.7	8.5	7.0	6.0	4.2	2.5	0.0	-2.2	90
A	6.8	5.8	4.7	3.9	2.5	1.1	-0.9	-1.8	83
B	3.6	3.2	2.6	2.0	1.0	-0.2	-2.3	-3.6	68
40%	11.2	10.2	8.9	8.0	6.4	4.8	1.5	-2.4	93
25%	7.3	6.6	5.7	5.1	4.1	3.1	0.8	-1.4	92
12%	3.6	3.2	2.8	2.5	2.1	1.6	0.5	-0.5	93

heavy rainfall days would be desirable as long as saturation did not occur. However, seeding effectiveness on such days is questionable (as assumed in the variable models) and undesirable if erosion is substantial.

Fig. 10 is based upon use of the variable-change optimum model and illustrates how the economic benefits may vary between individual regions. Thus, Fig. 10 shows that Region 8 has the highest median income benefit among the four regions shown, but its year-to-year gain has a substantially greater range. The differences shown in Fig. 10 are believed to be related strongly to the soil properties of the regions, and, to a lesser extent, with climatological differences in daily rainfall distributions within the state. Region 8 is located in southern Illinois (Fig. 1) where soil conditions are such that seeding-induced rainfall would be more helpful, on the average, than in the central protion of the state where Region 3 is located. However, frequent rains are needed in southern Illinois, so that the year-to-year effectiveness

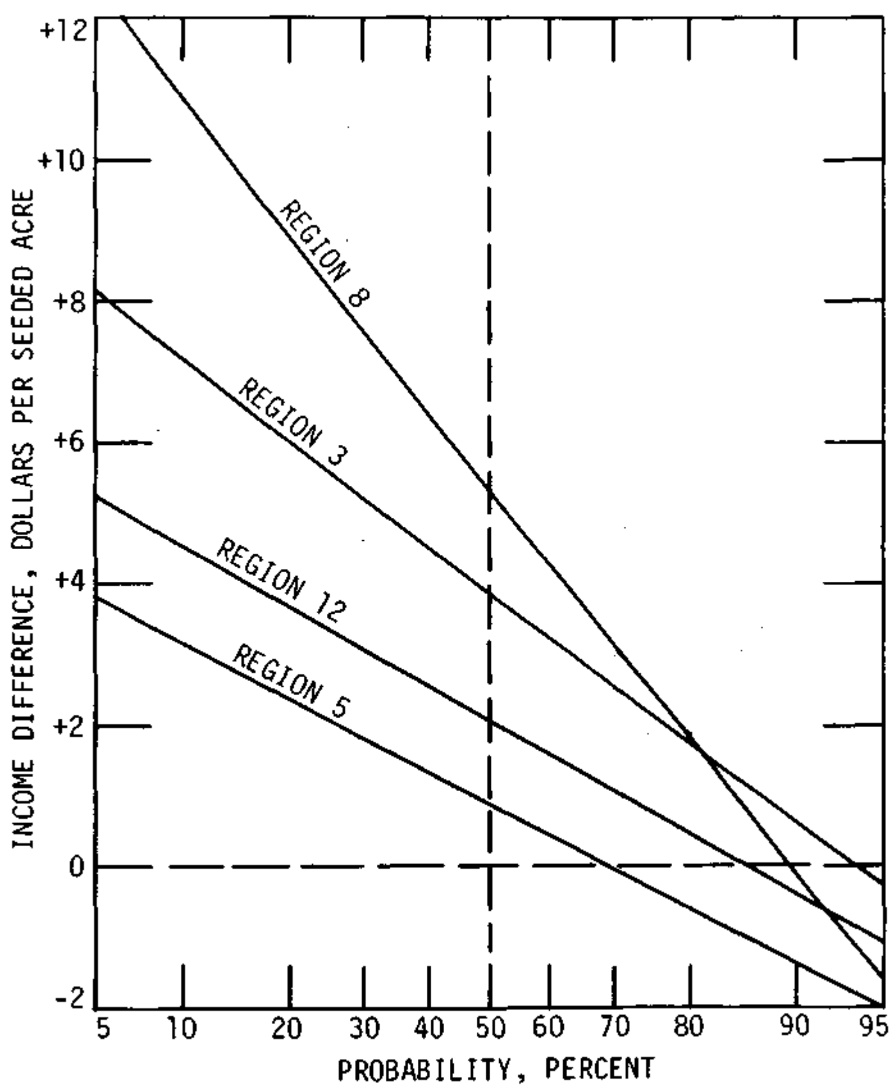


Figure 10. Variation of economic benefits between regions with variable-change models and optimum results

of the seeding model can vary substantially, based upon the time and intensity distribution characteristics of the naturally-occurring rainfall. Region 5 in extreme southern Illinois is in a poor crop-yield area in which seeding could only produce very modest gains and in which the presence of "wet" soils would make rainfall modification of questionable value in many years.

Up to this point, results of the economic benefits have been based upon a single-year analytical basis. As indicated earlier, similar analyses were made for 2-year, 3-year, and 5-year periods in which moving averages were used to obtain frequency distributions of yield benefits. Fig. 11 illustrates the differences in benefits when based upon a single-year analytical base and when averaged over periods of five consecutive years. This figure is based upon Model A applied to Region 11S. As expected, the range in income gains and losses is less when seeding results are averaged over a 5-year period. That is, the probability of a large gain is less, but the probability of a loss is also less when results are averaged over several years.

Detailed summaries of the frequency distribution of economic benefits (disbenefits) are provided for each model in each region and for assumed seeding operations of 1 to 5 years in Tables 27 to 63 in the Appendix. These can serve as a base for estimating the desirability of seeding in various sections of the state.

A basic finding that has emerged from the Illinois study is that strictly from the standpoint of probability of help or harm to corn and soybeans, it would usually be advantageous to initiate cloud seeding whenever a "dry spot" develops in the state. As shown in this report, the rain increase models are helpful the majority of the time over most of the state, even including relatively wet summers. For example, Model A, which normally produces moderate increases in the July-August rainfall, provided beneficial results in 77% of the years, on the average, for the state as a whole. However, this value ranged from near 50% to over 90% of the years among individual regions. Therefore, it is recommended that the detailed regional summaries in the Appendix be reviewed whenever seeding is contemplated in a particular region. The probability of success does vary considerably from the state average in several regions.

SUPPLEMENTARY STUDIES

Differential Effects of Seeding on Corn and Soybeans

As part of the research, analyses were made of the differential effects of cloud seeding on the two crops, corn and soybeans, when variable-change models are employed. This was done 1) to provide another measure of the relative effectiveness of the hypothetical seeding models, 2) to determine the frequency with which opposite effects would occur between the two crops within a given region, and 3) to ascertain whether one crop benefited most frequently in the opposite-effect years.

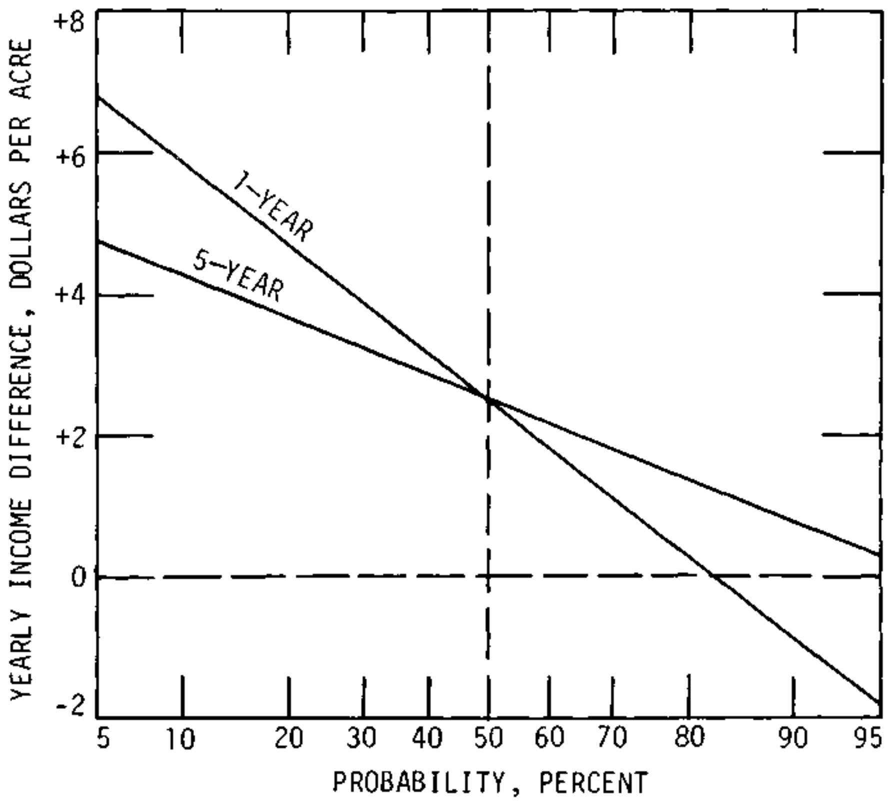


Figure 11. Comparison of income benefit probabilities with 1-year and 5-year seeding operations in Region 11S with Model A

Results for Region 11S with the three increase models (E, A, B), the cross-over model (C), and a decrease model (X) are summarized in Table 14. Detailed summaries for all regions are included in the Appendix as Tables 64 to 68.

Table 14 indicates results to be expected in Region 11S under the weather conditions experienced in the 1931-1968 period and with a 1968 technology capability. With Model E, the heaviest rainfall increase model, it was found that corn would have been helped in 36 of 38 years under the observed weather and assumed technological level. Similarly, soybeans would have benefited from application of Model E in 33 of the 38 years. In the 38-year period, both crops would have been helped 32 times (yield increase) and harmed only once (yield decrease). In 5 years, or 13% of the sampling period, opposite effects would have resulted from application of Model E. As shown in Table 14, corn would have been the crop helped in 4 of these 5 opposite-effect years.

Table 14. Frequency of years variable-change models would increase or decrease crop yields in Region US.

Seeding Model	Total number of years: Corn Helped	Corn Hurt	Soybeans Helped	Soybeans Hurt	No. of years: Both Helped	Both Hurt	Number of times helped in opposite effect years: Corn	Beans
E	36	2	33	5	32	1	4	1
A	31	7	32	6	26	1	5	6
B	26	12	28	10	22	6	4	6
C	16	22	12	26	6	16	10	6
X	3	35	0	38	0	35	3	0

The major difference between Models E and A is the number of opposite-effect years, 11 for A compared with the 5 for E. Proceeding to Model B, which produces less seeding-induced rainfall than Model A, fewer years with benefits were obtained, but still increased crop yields occurred in about 70% of the years. A reversal takes place from Model B to Model C, a cross-over model with respect to increasing or decreasing the July-August rainfall. With Model C, crops would be harmed more often than helped in a continuous year-to-year seeding program. As expected, Model X, a decrease model that would only be used knowingly in overly wet years, would have helped in only 3 of the 38 years for corn and not at all with soybean yields. This indicates quite strongly that decreasing rainfall through seeding would seldom help corn or soybean yields in this region in south central Illinois. Among the 13 regions, Model X was helpful, on the average, in 6 of the 38 years for corn and 8 of 38 years for soybeans (Appendix, Table 68).

Except for Model E, Table 14 shows a substantial number of years in which the increase models would have an opposite effect on crop yields in Region 11S. This illustrates one of the problems inherent in cloud seeding operations -- that is, one crop may be helped while another in the same area could be harmed. However, in part of the opposite-effect years in Region 11S both gains and losses were small, so that the differential effect was not a serious problem from consideration of overall economic benefits or disbenefits.

Economic Gains with Improving Seeding Capability

An analysis was made to determine the economic gains that would result from a progressively increasing capability to augment natural rainfall in the July-August period. For this purpose, a starting capability corresponding to Variable-Model C was assumed. As described earlier, this model resulted in a nearly equivalent number of rainfall increases and decreases in the naturally-occurring rainfall total for July and August when applied to the 1931-1968 data. The seeding effectiveness of the variable-change models from year-to-year is related to the distribution of daily rainfall amounts upon which these hypothetical seeding models operate. It was assumed that seeding effectiveness would gradually increase from that represented by Model C to Models B, A, and E.

Results of this analysis are illustrated in Table 15 for five regions selected to represent different crop-yield characteristics. Interpretation of Table 15 is illustrated by the following example. In Region 3, improving the seeding capability from C to B would result in a median income gain of $1.05 per seeded acre. Additional improvement from B to A would provide a median gain of another $1.05 per acre. Finally, improvement from A to E would add $1.10 per seeded acre. Thus, overall improvement from Model C to Model E would be expected to increase the average or median income by $3.20 per seeded acre in Region 3 over an extended period of time with the climatic conditions and technology levels used in the Illinois study.

Table 15 shows that the economic gains would vary substantially among regions if seeding effectiveness was progressively increased. Among the 5 regions , the greatest monetary gain is indicated for Region 10 in the northern part of the state, normally a high yield area, with an overall increase of $10.40/acre in progressing from Model C to Model E effectiveness. The least effect is in Region 12 in the extreme western part of the state with an overall gain of $2.55/acre. This region, which is also a relatively high yield area, lies in the belt of maximum thunderstorm activity in summer, and, therefore, is less likely to suffer from soil moisture needs than some other regions. The relatively large increase in Region US in south central Illinois occurs in an area in which soil conditions are such that frequent rains are needed to maintain adequate soil moisture, and the seeding-induced rainfall would be particularly useful. Corn and soybean yields in Region 11S average only 65-70% of those in the other four regions listed in Table 15.

Table 15. Comparison of median income gain with improving seeding capability.

Region	Model Sequence	Gain (Dollars) Per Seeded Acre
3	C-B	1.05
	B-A	1.05
	A-E	1.10
6	C-B	1.35
	B-A	1.60
	A-E	1.05
10	C-B	3.40
	B-A	3.40
	A-E	3.60
IIS	C-B	1.70
	B-A	2.00
	A-E	1.90
12	C-B	0.85
	B-A	0.90
	A-E	0.80
State Average	C-B	1.98
	B-A	2.15
	A-E	1.98

Comparison of Variable-Change and Constant-Change Models

Table 16 summarizes the results of a comparative analysis of the effectiveness of two types of hypothetical seeding models in Regions 10 and 11S. Region 10 was selected as representative of the high-yield regions in the northern part of the state, and Region 11S is representative of the relatively low-yield regions of southern Illinois. The comparison has been made between variable Model A and the 25% constant-increase model because over the 38-year sampling period, Model A has also averaged a 25% increase in July and August rainfall. The primary purpose of this particular 2-region analysis was to determine whether the differences in yields between the two models were related to the relative dryness or wetness of the July-August period.

Table 16 shows that the constant-change model was superior in both regions, based upon 38-year median and average yields. Results for the two regions show a poor relation between corn yield differences and departure from normal in both July and July-August total rainfall. Examination of data for the individual years did show a weak trend for the constant-increase model to be more effective in below-normal and slightly above-normal years and for Model A to do a little better in relatively wet years. This trend is related to the basic characteristic of Model A which results in decreasing seeding effectiveness with increasing daily rainfall with a cutoff at a daily amount of one inch. However, as shown by the correlation coefficients in Table 16, the overall relationship between yield differences with the two models and normality of naturally-occurring rainfall was extremely weak. Thus, in Region 10 the correlation coefficients of -0.38 and -0.46 indicate the yield differences to be inversely related to departures from normal in the July and August rainfall, but these correlation coefficients explain only 14% and 21% of the variance.

The foregoing comparative analysis emphasizes that there may be a substantial difference in seeding-induced yield changes between two types of seeding models, although their seeding-induced rainfall average is nearly equal when averaged over the long term. Thus, how the rainfall is increased will have an effect upon its benefits to crop yields. This needs to be known for accurate estimates of future benefits from rainfall modification.

Differences between equivalent variable-change and constant-change models in other regions can be obtained from Tables 8 to 26 in the Appendix, which show frequency distributions of corn and soybean yield changes in all regions with the two types of models. As indicated earlier, the average increase in July-August rainfall is similar between Model B and a 12% constant increase and between Model E and a 40% constant increase.

Relation Between Rainfall Normality and Seeding Effectiveness

Two variable-change increase models, A and B, and two decrease models, X and Y, were used to investigate the relationship between the departure

Table 16. Comparison of seeding results for corn with variable Model A and 25% constant-increase model.

	Region 10	Region 11S
Average yield difference (bu/acre), 25% - A	+2.1	+1.2
Median yield difference (bu/acre), 25% - A	+1.1	+0.6
Correlation Coefficients		
Yield difference vs. departure from normal of July-August rainfall	-0.38	+0.11
Yield difference vs. departure from normal of July rainfall	-0.46	-0.39

from normal of July-August rainfall and seeding-induced yield changes for corn in Region 11S. For this analysis, the data were grouped into years with above and below normal rainfall in the July-August period. The increase models, A and B, would be expected to be positively correlated with departure from normal in years with below-normal rainfall and negatively correlated in years with above-normal rainfall for July and August. The opposite trend would be expected in the above-normal years; that is, X and Y should be positively correlated and A and B should be negatively correlated.

Results of the correlation analyses are summarized in Table 17. The expected trends with respect to positive and negative correlation were found. Although the trends are reasonable with respect to sign, the degree of correlation is relatively weak between rainfall normality and seeding-induced yield changes. From this analysis, it would appear that the overall departure from normal of July-August rainfall is not a good indicator of the expected yield gains from seeding. Other factors, such as the time distribution of the naturally-occurring rainfall and the distribution of storm or daily rainfall with respect to volume and intensity contribute to the seeding effectiveness in any given year.

Table 17. Correlation for corn between seeding-induced yield changes and normality of July-August rainfall for selected seeding models.

	Correlation coefficient for given data stratification	
Model	Above-normal years	Below-normal years
A	-0.37	+0.43
B	-0.13	+0.31
X	+0.27	-0.10
Y	+0.33	-0.40

Effect of Seeding Models on Variance

Calculations of the change in variance with application of the various hypothetical seeding models were made to aid in evaluating seeding benefits. For example, if seeding provided no benefit other than reducing the natural year-to-year variation in yield, it might be useful. Calculations were made for Regions 3, 4, 10, 11S, and 12 to obtain a sampling in different areas of the state and for regions of various sizes. In these regions, variable-change models A, B, C, X, and Y were tested on corn, along with constant-change models for 12%, 25%, -15%, and -30%.

Results of the analysis are summarized in Table 18, in which the variance is shown for the equation-predicted yields with 1) no seeding, and 2) after application of each seeding model to the 38-year sample. With all seeding models there is a trend for the variance to increase from that obtained with the non-seeded yields from the prediction equations. However, in most cases the increase is not large, and this is reflected in the median and average values for the five regions. There appears to be no marked superiority for any seeding model with respect to minimizing the variance. There is considerable fluctuation in the variance between regions. This is not surprising since soil properties, climatic conditions, and technological improvements can vary between regions and these factors can affect the year-to-year variation in crop yield.

Overall, it was concluded that seeding would not substantially alter the natural variance of regional corn yields, although the net effect in most regions would be a slight increase in the year-to-year variability of yields.

Table 18. Effect of seeding on variance of corn yields (bu/acre) in selected regions.

Region	No seeding variance	Variance for given seeding model: Variable-change models A	B	C	X	Y	Constant-change models +12%	+25%	-15%	-30%
3	75	118	97	82	79	64	128	162	97	89
4	175	199	180	173	174	170	191	233	169	165
10	168	182	202	213	253	230	158	139	179	174
US	136	124	136	140	146	147	134	137	139	138
12	84	88	87	85	90	86	85	85	83	80
Median	136	124	136	140	146	147	134	139	139	138
Average	128	142	140	139	148	139	139	151	133	129

Comparison of Interaction and No-Interaction Equations

Predicted annual corn yields from the various regions obtained with weather-technology interaction and no weather-technology interaction equations were compared to determine whether significantly different values were obtained. In this comparison, yield differences in each of the 38 years (1931-1968) were obtained between the actual average yields recorded in each year for each region and the yields calculated from each of the two equations. Differences between the calculated yields from the two equations were tabulated also.

For each of the three sets of differences, means, medians, and frequency distributions were obtained in each region. For the 38-year sampling period, the median difference for all regions combined was 0.3.bu/acre between the actual and prediction equation values and 0.1 bu/acre between the two prediction equations. Among regions, the median difference between the actual and the interaction values ranged from -0.3 to +0.9 bu/acre. Similarly, the median ranged from -0.7 to +0.7 for the differences between actual and no-interaction values and from -0.5 to +0.3 between the interaction and no-interaction values. From consideration of the median differences, there appears to be little difference in the prediction efficiency of the interaction and no-interaction equations. The same conclusion was reached from evaluation of the three sets of average differences which showed even smaller variations than the medians.

Next, the frequencies with which each set of differences equalled or exceeded selected values were calculated for each region. In general, the results indicated a slight superiority for the interaction over the no-interaction equation. This has been brought out in Table 19 in which all differences for the 13 regions have been combined into a single frequency distribution. In this table, the percent of the differences equalling or exceeding 1, 2, 3, 4, and 5 bu/acre are shown for each of the three comparisons. The number of occurrences of relatively large differences was somewhat greater between the actual and no-interaction predicted values than between the actual yields and the interaction predicted yields. The lack of major differences between the two prediction equations is indicated by the fact that the predicted values differed from each other by less than 1 bu/acre in 55% of the cases.

Based on the frequency of relatively large differences of 3, 4, or 5 bu/acre, the prediction equations showed the best correlation with actual yields in Region 8 in the southwestern and extreme southern part of the state, whereas the largest differences occurred in Region 6 in the central part of the state. For example, the differences between actual yields and the interaction predicted yields equalled or exceeded 5, 4, and 3 bu/acre, respectively, in 0, 3, and 6 years during the. 38-year sampling period in Region 8. In Region 6, these differences between actual and predicted yields were equalled or exceeded in 9, 10, and 24 years, respectively.

The interaction equations were selected for use in the regional computations because of 1) their slight superiority as indicated in the above comparisons, and 2) physical considerations which would indicate that crop yields would be affected to some extent by temperature and precipitation interactions during the growing season.

Table 19. Comparison of prediction efficiency of interaction and no-interaction equations for corn after combining all regions.

Difference equalled or exceeded (bu/acre)	Percent of total occurrences for given comparison		
	Actual minus interaction yields	Actual minus no-interaction yields	Interaction minus no-interaction yields
1	77	75	45
2	55	57	19
3	34	37	8
4	19	25	3
5	12	16	2

Technology-Economics Discussion: Test of an Alternative to 1968 Technology

The difficulties of taking into account the role of technology in estimating crop yield response have been mentioned previously in this report. As indicated earlier, the assumption of 1968 technology was in part dictated by the lack of an effective means of predicting future technology and also whether such technology will interact with rainfall augmentation in the same way as during the period of observation. Nevertheless, it is of interest to examine the effect on yield response of a simple extrapolation of the 10 years of technological change. The change in response of corn and soybean yield to one inch of precipitation from such an extrapolation is presented in Table 20. Our expectation would be that general improvements in technology would increase the response of yield to precipitation. Although this is the general pattern, there are a number of exceptions. For example, in Region 1, the effect of 10 years of technological change was to <u>reduce</u> the response of corn yield to one inch of July precipitation by 0.77 bushels (Table 20). Of the 13 regions the expected complementarity between technology and response to precipitation occurred in 18 out of 26 cases for corn and 15 out of 26 cases for soybeans.

Table 20. Effect of 10 years of technological change on yield response to 1 inch of rainfall (temperature at 1931-1968 mean value).

Region	Corn		Soybeans	
	July	August	July	August
	- - - - - - - - - bushels per acre - - - - - - - - -			
1	-0.77	0.45	-0.52	0.10
2	0.12	0.17	-0.68	-0.36
3	0.42	0.30	-0.33	-0.50
4	0.19	0.79	-0.02	0.24
5	-0.25	-1.10	0.02	-0.41
6	-0.31	1.10	-0.36	0.45
7	1.55	1.91	0.59	0.05
8	2.22	-0.32	0.38	0.03
9	2.13	2.15	0.60	0.23
10	3.03	1.11	-0.11	0.39
11N	1.01	0.99	0.18	0.33
11S	0.66	-0.01	-0.14	0.52
12	-0.07	-0.18	0.03	-0.10

WEATHER MODIFICATION CONSIDERATIONS

Analysis of Seeding Costs

Economic evaluation of seeding benefits requires information on seeding costs. Therefore, an effort has been made to obtain such information through every possible source, since there appears to be little published on this subject. Very little published information is available because commercial seeding operators normally do not publish such information. However, some information has been gleaned through personal conversations, 1 or 2 technical papers, and a few oral presentations of papers.

The costs normally involved are 1) a profit of unknown dimension; 2) a project meteorlogist who forecasts and directs daily operations (on site or remotely); 3) seeding equipment that may be ground-based generators and/or aircraft equipped with seeding devices; 4) personnel to operate and service all equipment (although some may be subcontracted to locals or handled by volunteers); and 5) miscellaneous charges for housing and for transporting staff and equipment to the site. No breakdown on these costs as a part of the quoted total costs has been found.

The readily available information at this time is summarized in Table 21. Costs for hail seeding projects are considered viable for rain-increase projects since both are 2- to 3-month warm season efforts requiring identical equipment and activities on most precipitation days. From this table, it appears that the cost is approximately $0.05 per acre per year for rain-increase operations, increasing to about $0.15 for hail suppression. In either case, the cost is relatively small compared with the median added income per acre discussed earlier in this report.

Additional information on commercial seeding costs was obtained in a conference on June 25, 1970 with Mr. Thomas Henderson, Atmospherics Incorporated, who has had extensive experience in commercial seeding operations. He indicated that the usual method of calculating seeding costs is to set up a box encompassing the target area and base costs upon size of area and total number of acres cultivated. From one operational site, an area of approximately 3000 mi^2 can be seeded. Three aircraft and a radar should be integral parts of the operational equipment for a summer cumulus seeding project. Radar is very essential to optimize regions of attack within the target box, and one radar can observe 2-3 aircraft in a 3000 mi^2 area.

As the number of unit areas are increased in number, seeding costs decrease. Seeding costs per unit time also decrease as the operational period increases. Thus, within a given year, the cost per month for a 3-month operation would be less than for 1 month. Similarly, a seeding contract over several years can be considerably cheaper than a 1-year contract. The higher price for shorter periods is due to certain basic costs involved in every seeding operation, regardless of its length. The base price is a major portion of the total cost of a seeding operation.

Table 21. Estimates of seeding costs.

Source of information	Project purpose	Project location and duration	Data obtained	Money source	Area seeded mi^2	Portion of area supporting project	Equipment	Period of operation	Cost per acre per year	Annual total costs
Project Met. Krick Assoc. (verbally)	hail supp.	Alberta, Canada (9 years)	July 1968	Local farmers groups	2000	about 50% .	4- airplanes 180 GG*	5/15-8/15	15¢	$100,000
Schleusener (ASCE paper at Chicago)	rain increase	Great Plains	Oct. 1969	Not indi-cated	2500	Not indicated	1 airplane	3 months	5¢	75,000
Dennis at S.D. (verbally)	hail supp.	SW S. Dakota (3 years)	July 1968	Levy on local farmers	about 1500	100%	1 airplane	May-July	10¢	96,000
Howell (verbally proposed)	hail supp.	Illinois (5 years)	Nov. 1966	Tax levy plus ins. reduction	3000	about 100%	2 airplanes 100 GG*	June-Aug.	16*	300,000
Newspapers £.County Agent	rain increase	Illinois (1 year)	Aug. 1964	Contri-butions	720	100 people	7 GG"	2.5 mos.	1.5¢	6,500
Henderson (Atmos-pherics Incorporated) (verbally)	rain** increase	Illinois (1, 2, and 5 years)	June 1970	Not"" applicable	3000	Assumed to be all	3 aircraft 1 radar	2 months	5* (1 yr)	104,000

"GG = ground generator
""Bid on hypothetical project

July-August Dry Period Climatology

A climatic study of July-August dry periods in Illinois during the 1931-1968 period was performed to gather information on the time-space variations of areas with the greatest need agriculturally for rain augmentation. Although a comprehensive meteorological analysis of these was not performed, the climatic results have usefulness in assessing certain design and economic factors of summer weather modification projects in Illinois. They are also of interest in understanding certain climatic aspects of these dry periods, such as the presence of long-term trends in their occurrences. Although results of the Illinois research have shown that economic benefits would come from added rainfall in the many "near-normal rainfall" summers, seeding would have its greatest economic benefit by enhancing rain in dry July-August periods.

In this climatic investigation, dry periods (or dry areas) were defined arbitrarily as July-August periods with less than 50% of the normal 2-month rainfall. Huff and Changnon's (1963) study of precipitation droughts in Illinois showed that 3-month droughts achieving a percentage of 50% of normal rainfall or less represented a point event with a recurrence interval of once every 2 to 3 years. July-August rainfall normals were computed for 54 weather stations with complete records in this 38-year period, and then the statewide pattern of average July-August rainfall was developed. Individual isohyetal maps based on July-August rainfall totals for each year in the 38-year period were prepared. Comparison of these yearly maps with the 38-year average pattern allowed assessment of those areas where amounts were 50% or more below normal. Each of these areas was then planimetered to obtain the areal extent, and the position of its center was plotted on another map. A total of 75 distinct "dry-areas" were found in the 38-year study period.

The results derived for dry areas (periods) are presented to describe various temporal and spatial aspects in the dry-period distributions. Temporal analyses performed included the statewide and regional time series of dry periods during the 38-year period, their tendency for persistence in each region, and the annual frequency in Illinois. Areal information investigated included county and regional frequencies and information on the areal extent of the dry areas. Also, the frequency of rain days of different magnitudes occurring with these July-August dry periods was investigated.

The average July-August rainfall in Illinois is 6.4 inches, ranging from 5.9 inches in the south-central area to 8.1 inches in northern Illinois. Fifty precent of normal July-August rainfall in most locations in Illinois ranges from 3 to 3.5 inches.

Temporal variations. Certain areal and temporal frequency information on the dry periods (areas) appears in Table 22. The 38-year state total was 75 dry areas, producing an annual average value of 2 dry areas per year. The distribution of these dry periods per year is also shown, indicating that 10 years of the 38 had no dry areas, 21 of the 38 years had 2 or more dry areas, and in 2 years (19 53, 1964) there were 5 or more distinctly separate dry areas within Illinois.

To inspect for possible long-term trends in July-August rainfall, the maximum and minimum 2-month amounts anywhere in Illinois in each year were determined. These extremes are plotted on Fig. 12, along with the statewide average of 6.4 inches. Dashed lines were drawn at 2 inches and at 15 inches to reference variability with time. Inspection of the curve of the lowest statewide values reveals a distinct upward shift with time. In the first 19 years of the 38-year period, 10 of the lowest point values in Illinois were less than 2 inches. Thus, more than 50% of the July-August periods in the 1931-1949 period had points with less than 2 inches. In the second 19-year period, 1950-1968, only 2 years experienced July-August totals of less than 2 inches. Although the upward trend in July-August rainfall values found in the lowest values is not as apparent in the highest values (Fig. 12), it can be noted that 7 years of the first 19 had values that were 15 inches or higher, whereas in the most recent 19 years studied, 11 years had 15 inches or more. This set of statewide extremes for July-August rainfall does suggest a "better" rainfall regime in the most recent 15-20 years.

Table 22. Statistics on dry areas (- 50% of normal rainfall) in July-August period of 1931-1968

<u>Frequency of Areas</u>

1. 38-year state total = 75
2. Annual average = 2
3. Number of years in Illinois with:

No dry areas	= 10
1 or more	= 28
2 or more	= 21
3 or more	= 14
4 or more	= 9
5 or more	= 2

<u>Sizes of Individual Areas (mi^2)</u>

Average	= 1,461
Median	= 435
Largest	= 19,200
Smallest	= 45

50% occurred in range between 240 and 960 mi^2.

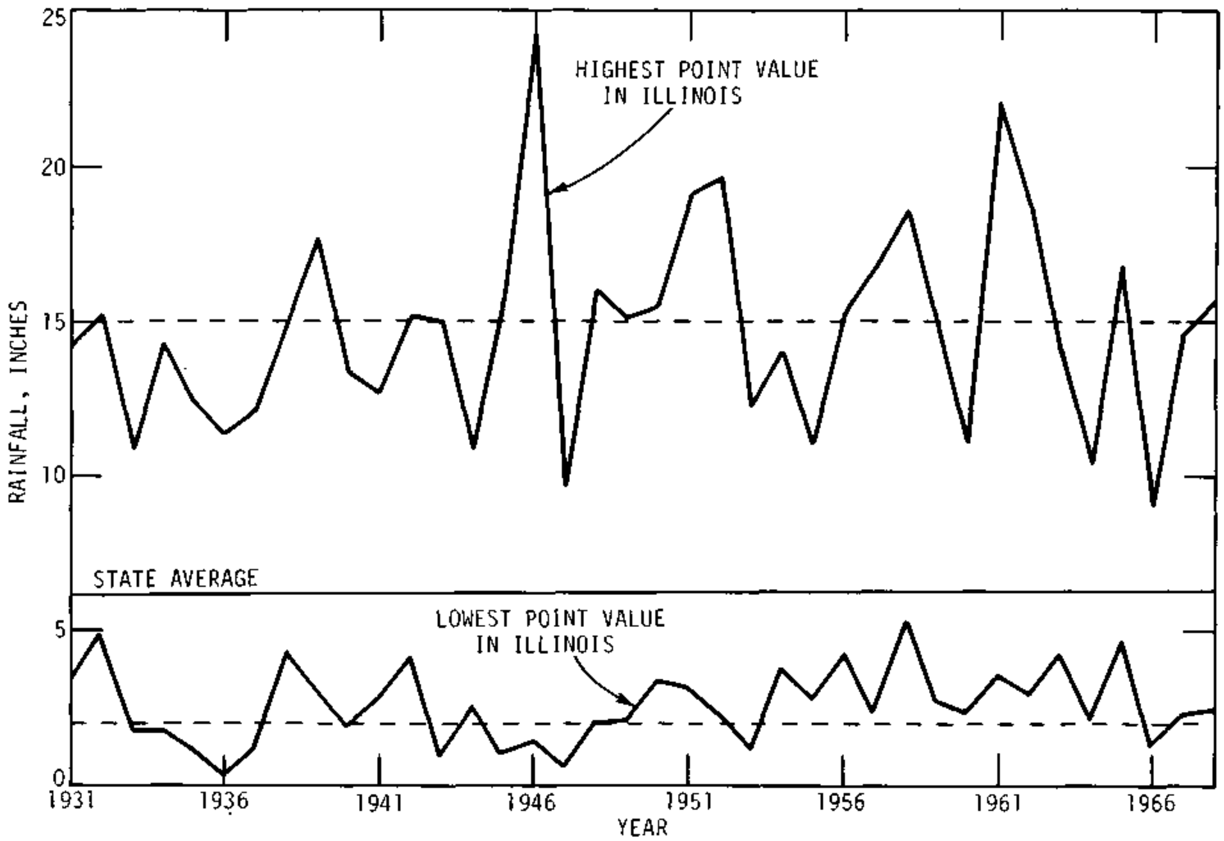


Figure 12. Distribution of maximum and minimum 2-month rainfalls

The temporal distribution of dry areas were determined for those in each of the 13 crop-weather regions. Results for three of these regions are portrayed in Fig. 13. The data for Regions 3 and US substantiate the indications shown in Fig. 12 with decreasing frequencies of dry areas with time. For instance, 7 cf the 12 dry areas that occurred in Region 3 occurred before the middle of the 1931-1968 period, and in Region US, 10 of the 17 dry periods there occurred before 1950. Region 2, which has had fewer dry areas than Regions 3 and US with a total of only 9, shows a somewhat different distribution with 5 of its 9 dry areas during the last 19 years. However, it should be noted that in these regions shown on Fig. 13 and all others in Illinois, the number of dry periods has dramatically decreased since 1957. Most of the 1931-1968 dry-period occurrences were concentrated between 1933 and 1955. Furthermore, there has been lack of any widespread occurrence in the recent 15 years. For instance, 1943, 1945, 1947 and 1953 had dry areas in all three regions (Fig. 13), but no comparable widespread dry area has occurred in all 3 regions since 1953.

Another way of inspecting the time (and space) variations of dry areas in the crop-weather regions is to plot their centers within the regions, as illustrated in Fig. 14 for Regions 2, 3, and US. Here the yearly value is plotted within the region at the point where the lowest rain value occurred within the below-normal area. Inspection of the general placement of these annual values reveals that even within the 3 regions, areas of extreme dryness seem to be non-randomly distributed. For instance, in Region 3 most of the extreme dry areas were in the NE or extreme SW. Among the more interesting and useful operational aspects of the results in Figs. 13 and 14 are the temporal distributions of dry periods in each area. Note how most (10) of the dry areas in Region US occurred during a 13-year span from 1940 through 1953. Similarly, half of the 12 dry periods in Region 3 occurred in the 1940-1947 period, and even in Region 2, 6 of the 9 dry areas were concentrated in the 14-year period beginning with 1943. Hence from an operational seeding standpoint, it appears that once a region of Illinois has had 3 dry periods in a 5-year period, it's likely that the need for operations there would occur frequently over a 7- to 14-year period. This tendency for repeated dry areas in relatively small regions of Illinois is of considerable climatic interest and cannot be explained with available data.

To investigate the possibility of detecting (and predicting) July-August dry periods (areas), the amounts of rainfall in the July 1-15 period for the 75 dry areas were calculated. Each areal mean amount was expressed as a percent of the normal July 1-15 amount for the particular area of the dry region. Averaging of these 75 regional percentages for July 1-15 rainfall indicated a mean value of 37% (about 0.6 inch) of normal with extremes varying from 0% to 130%. Rainfall in the July 1-15 period (of July-August dry periods) was 10% or less of normal in 19 of the 75 dry periods, 25% or less in 34, and 50% or less in 52 (70%) of the 75 dry periods. Rainfall in July 1-15 exceeded 100% of normal in only 2 dry periods.

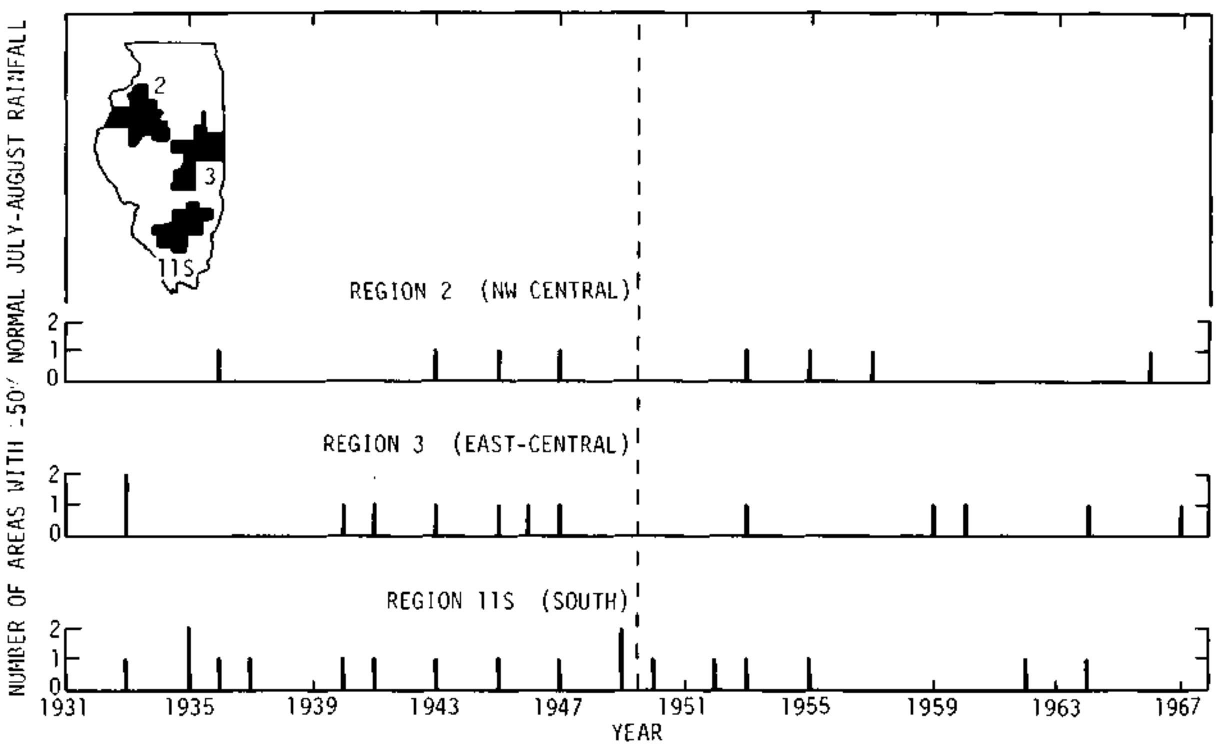


Figure 13. Regional distribution of dry areas

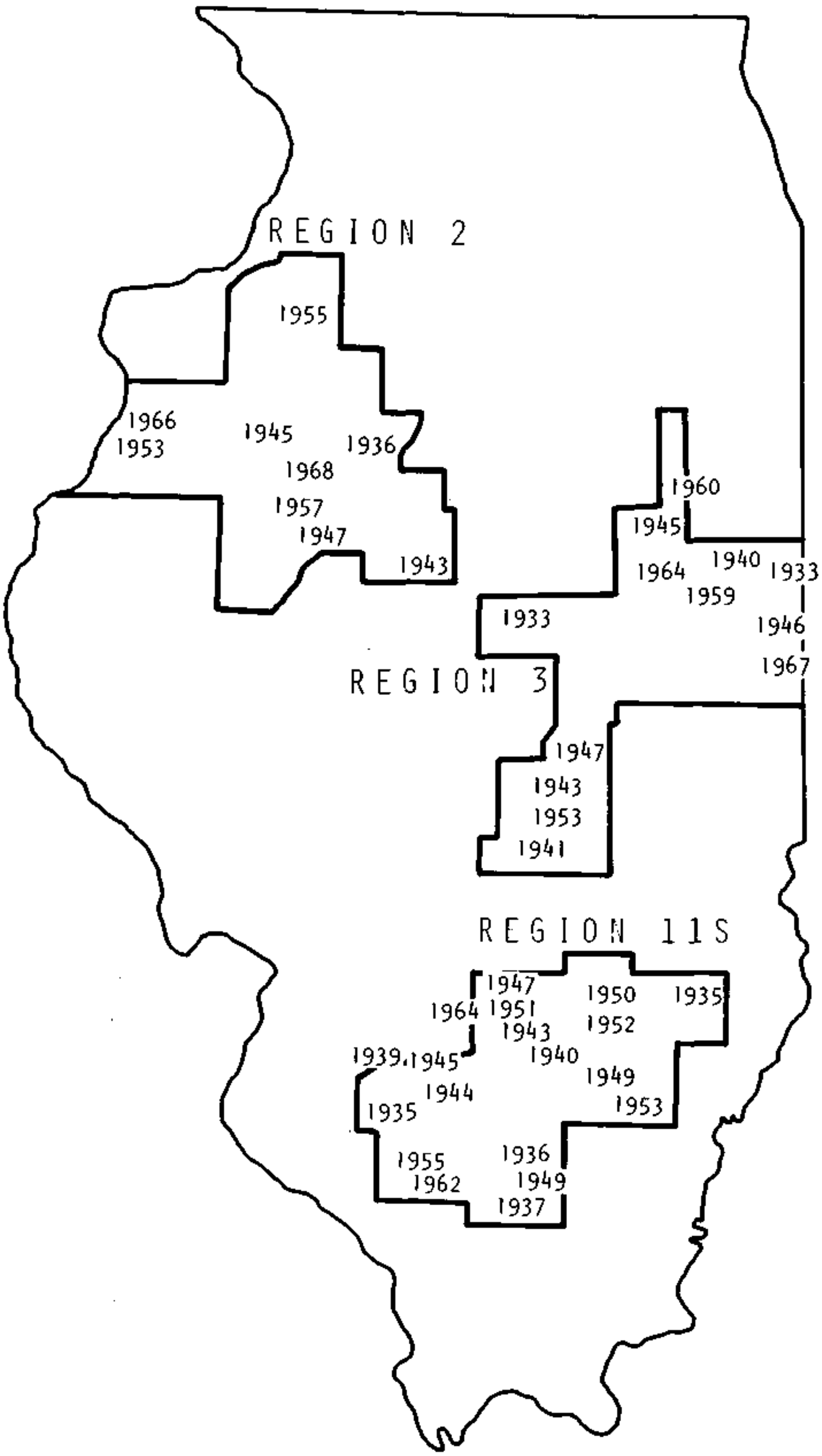


Figure 14. Dry-area centers within Regions 2, 3, and 11S

A second investigation using long-term data from 4 stations was performed to examine the relationship between July 1-15 rain amounts and July-August rainfall. This analysis revealed that only 23% of all July 1-15 periods with rain 537% of normal (the average for all 75 dry periods) were associated with dry periods (July-August totals 550%). However, this more meaningful analysis of the use of July 1-15 period rainfall as a predictor revealed that 94% of all July 1-15 periods that had rainfall ≤50% of normal (about 0.8 inch, or less) were associated with July-August totals ≤75% of normal. When the July 1-15 rainfall was >50% of its normal, there was no useful (predictive) relationship with the July-August totals.

Spatial characteristics. Planimeterming of the 75 dry areas yielded the results shown in Table 22 regarding their sizes. The distribution was sufficiently skewed so that the average areal extent was considerably larger than the median value which is considered more realistic. The median of 435 mi^2 is just slightly less than the average size of an Illinois county which gives some perspective as to the smallness of the typical July-August dry area. The largest dry area of 19,200 mi^2 occurred in 1936. This area represents 34% of the total state area, whereas the median dry area is slightly less than 1% of the total state area. These areal extent values, coupled with the frequency of dry areas by years shown in Table 22, allow an estimation of operational aspects for rain enhancement if all dry areas were to be the focus of rain enhancement projects.

The extent of the July-August dry areas in each year were summed and used to develop statewide totals. These totals are shown in Fig. 15. Four years (1936, 1945, 1947, and 1953) had exceptionally large areas of dryness. Interestingly, most of the years with extensive dry areas in July-August occurred prior to 1954 and most of them were concentrated between 1933 and 1947. This time-area graph also supports the results shown in Figs. 12-13 that indicate a lessening of dry area frequency and areal extent during this 38-year period.

To investigate the areal distribution of the July-August dry areas , the number of times each county was either partially or totally within a dry area was tabulated by counties for the 38-year period. Iso-frequency lines based on county results are shown in Fig. 16. Region 11S, where corn yields are very dependent on July-August rainfall, is also denoted in the figure. Inspection of the statewide pattern reveals that highest frequency of dry areas occurs in a northwest-southeast section across southern Illinois. Isolated high frequencies of dry areas exist in western and east central Illinois. Steep gradients from these three high frequency areas to areas of low frequency can be found. For example, 9 dry areas were identified in Shelby County in south-central Illinois, but less than 3 were found in counties located just 30 miles NE of there. Counties in extreme northern Illinois, northeastern Illinois, and extreme southern Illinois had very infrequent July-August dry periods.

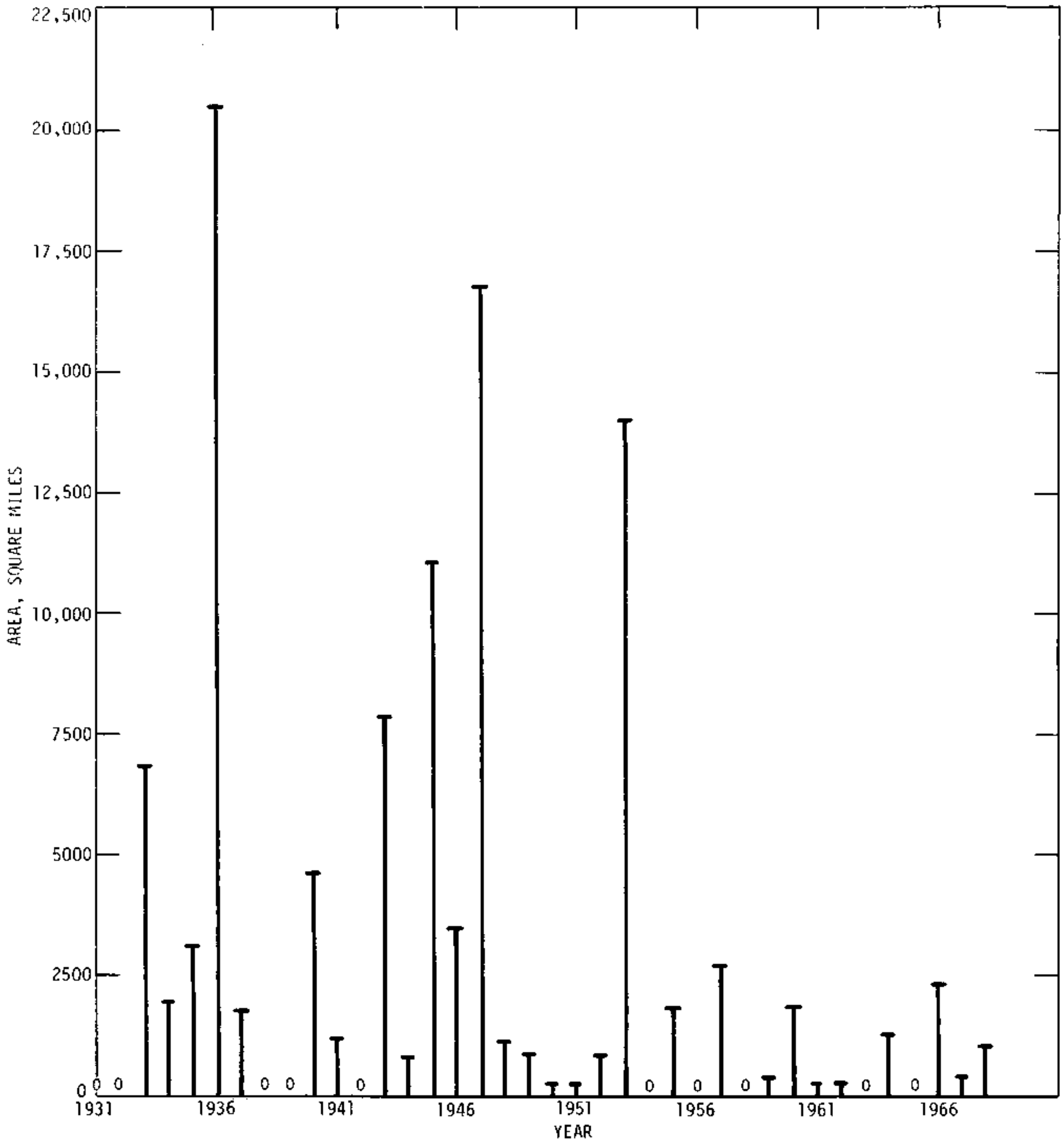


Figure 15. Extent of July-August dry areas

Inspection of Fig. 16 reveals that operational rain enhancement projects oriented to the occurrence of dry areas should exist in the southern half of Illinois, and probably within the area where frequencies of dry areas equal or exceed 6. Region US with 17 dry areas in the 38-year period led all other crop-weather regions in the frequency of dry areas and would appear to be the optimum rain enhancement area for operations undertaken to determine the value of July-August rain enhancement to agriculture.

Rain-day frequencies in July-August dry areas. An important question relating to the dry areas and their potential seedability (enhancement versus initiation) concerns the frequency of rain days during their occurrences. Hence, an analysis was made of the frequency of rain days using all the stations with 50% or less of normal July-August rainfall in the 75 dry periods during the 1931-1968 period. Rain days were defined at 3 levels: 0.1 inch or more, 0.25 inch or more, and 0.5 inch or more per day. Normal frequencies of these days in July-August, as based on data for the 1901-1962 period at the 54 stations, were computed for these 3 rain-day levels at each station. The long-term point averages are 5 to 6 days in July-August with 0.1 inch or more, 3 to 4 days across the state with 0.25 inch or more, and 2 to 2.5 (5 days in 2 years) of 0.5 inch or more. For each dry period, the actual number of rain days in each level was determined at each station, and these point values for all stations in the dry area were averaged. Thus, dry-area averages for 0.1-inch days, 0.25-inch days, and 0.5-inch days were established for each of the 75 dry areas. These actual dry-area averages were then expressed as a percent of the average of the normals of the stations in that particular drv area.

The results for this analysis are summarized in Table 23. The results show that the mean and median percentages of the averages for both the 0.1-inch and 0.25-inch classes were above normal. However, these were below normal for the 0.5-inch rain-day averages. The number of the 75 dry-area averages that were above 100% of the long-term normal, and the number that were equal to or less than 100% of normal are also shown in Table 23. Here it is shown that 50 of the 75 dry areas had 0.1-inch frequencies that were above 100%, whereas 72 of the 75 dry areas had frequencies of 0.5-inch rain-days that were 100% or below.

Table 23. Rain-day frequency information for 75 July-August dry areas (550% of normal), 1931-68.

	≥0.1 inch	≥0.25 inch	≥0.5 inch
Mean (%) of 75 dry-area . averages	122	105	69
Median (%) of 75 dry-area . averages	120	111	89
Number times dry-area average >100% of normal	50	37	3
Number times dry-area average ≤100% of normal	25	38	72

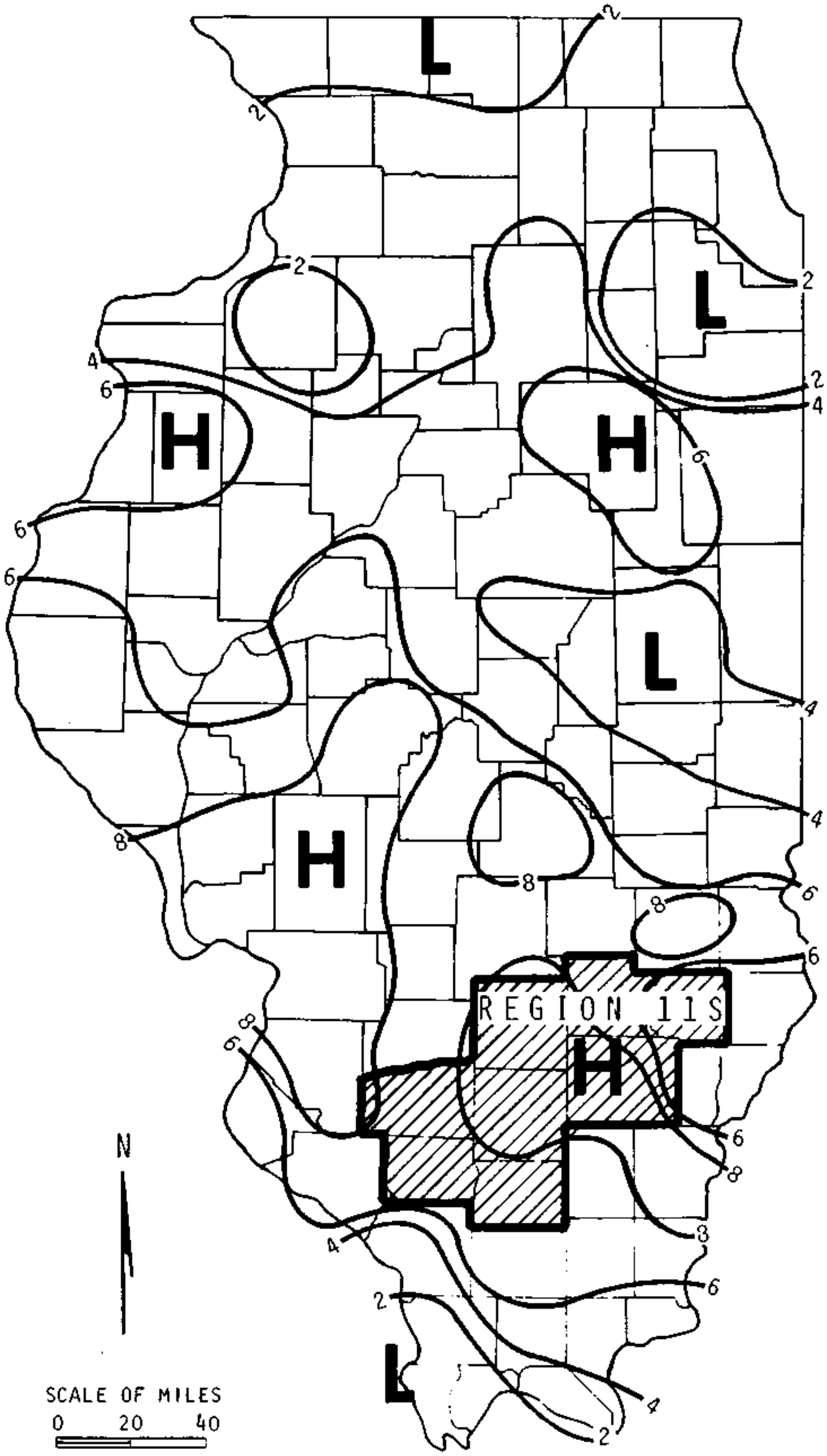


Figure 16. Frequency distribution of July-August dry areas

The results definitely suggest that there is no lack of light rainfall days in Illinois dry areas, but there is a distinct lack of 0.5-inch raindays, a condition noted in a study of Illinois droughts (Huff and Changnon, 1963). Therefore, the occurrence of July-August dry areas is related to the lack of moderate to heavy rainfall days and this does not stem from a lack of rain conditions, as revealed by the frequency of light raindays. More likely, the dry areas result from inefficient operation of the physical and dynamical processes in the cloud systems moving over the area, which, in turn, could be related to mesoscale temperature and evaporation processes at the surface. Another factor could be rapid storm motions across the dry area such that relatively heavy amounts do not occur. As a result of these findings regarding dry-period climatic properties during July-August dry periods in Illinois, it appears reasonable to attempt rain enhancement by seeding on days with naturally-occurring rainfall in efforts to increase light rainfalls into moderate to heavy daily amounts.

Conclusions. Review of the results shown by this analysis of July-August dry periods reveals that there has been a general statewide decrease in their frequency and areal extent during the 38-year study period. A non-uniform time distribution of dry areas in Illinois existed during this period in Illinois, and suggests that 10- to 15-year periods of frequent dry areas similar to that in the mid 1930's and late 1940's will occur again in the future. Comparison of the temporal variations in dry areas between the crop-weather regions shows there is great areal variability across Illinois, and suggests that mesoscale conditions conducive to the dry areas vary across the state in patterns that have yet to be ascertained. There is a distinct tendency within most crop-weather regions for dry periods to develop and occur repeatedly during a period of 7 to 14 years in length, and then essentially not to occur for periods of 5 to 15 years. In general, there seems to be a tendency that if a dry area has occurred within Illinois there will likely be one or more others within the state during the same year. If rainfall enhancement projects are geared to dry-area operations in Illinois, these temporal considerations will be important in planning for the type of seeding facility required.

It is important also to recognize that such summer dry areas are generally small in areal extent, with a size of the average Illinois county. However, in some years the dry areas are quite extensive so that occassionally 20% or more of the state experiences dry areas in the July-August period. In general, dry areas are most frequent in the southern half of Illinois with counties in south-central Illinois being most subject to dry conditions. Areas in extreme-northern and extreme southern Illinois experience dry periods much less frequently. If mobile seeding operations are possible, and if operations in below-normal rainfall areas are deemed desirable, it does appear possible to detect impending below-normal (<75% of normal) July-August rainfall with a high degree of success by monitoring the amount of rainfall during the first 2 weeks of July.

Analysis of rain-day frequencies during the dry periods in Illinois suggested that there is not a lack of light rainfall days, but rather a distinct lack of moderate to heavy rainfall days. Thus, seeding operations can be successful if existing rainfall can be enhanced, rather than attempting to produce rain on days with no naturally-occurring rainfall.

Prediction of July-August Rainfall Amounts

The results presented for the various hypothetical seeding models clearly revealed that it would be very useful and important to know in advance the amount of rainfall expected in the July-August period, or in either of these two months. Such information would permit the utilization of the optimum seeding model (including no-seeding) for any given summer and region. Obviously, forecasting technology now or in the foreseeable future is not capable of predicing the July and/or August rainfall amounts 30 to 60 days in advance.

The need for predictive knowledge led to a limited climatological study at 5 locations (each with long records) of the 1-month relationships in monthly rainfall and mean temperatures for June-July and for July-August. That is, the purpose was to determine from past data the July rainfall and temperature conditions following various June rain and temperature conditions, and, similarly, those of August with respect to July. If non-random relationships existed, conditional probability forecasts could be derived using, on June 30 or July 31, knowledge of the past month's weather conditions. Study of May plus June conditions with respect to July plus August conditions was not attempted.

At each of the 5 stations (all had 54 years or more of record), the monthly (June, July, and August) rain and temperature data for each year were classified and divided into thirds: the above normal third, the near normal third, and the below normal third. This meant that there were 9 possible types of monthly weather conditions. A wet month (above normal third in rain) could be with "hot" temperatures (above normal third in temperature), with near normal temperatures, or with cool temperatures. Similarly, the near normal rainfall class could be with these same three temperature classes as could the dry rainfall months. Thus, a matrix consisting of the 81 possible combinations (9 in June and 9 in July) were developed for June and July, and matrices for the 81 possible combinations were done for July and August.

The frequency distributions of the various June-July relations and July-August relations for 5 of the crop-weather regions are shown in Table 24, along with the levels of temperature and rainfall resulting from separating the mean monthly temperatures and total rainfall values into thirds.

Probabilities can be derived from the various frequencies shown in Table 24. For example, one useful operational seeding situation would concern, given that a wet July has occurred, what will August experience? In other words, could or should the operation quit efforts to enhance rain in August or should it try to suppress potentially heavy rainfall in August? The probabilities for the 3 possible classes of wet July (wet-hot, wet-normal, and wet-cool) appear in Table 25. If the probabilities were evenly distributed

Table 24 a. Region 10 (Aurora) monthly weather relationships, 1901-1962.

JUNE		JULY								
Rain	Temp	Rain	Wet			Normal			Dry	
		Temp	Hot	Normal	Cool	Hot	Normal	Cool	Hot	Normal	Cool
Wet	Hot			1		1				2	
	Normal				1			2	2	3	
	Cool			2	2		1	2	1		1
Normal	Hot		1	1		1			2	2	
	Normal		1				2			1	2
	Cool		1	2	2	1		1			
Dry	Hot		1	1		4	1	1	1		
	Normal			1	1	1		2			2
	Cool			1	2				2		

JULY		AUGUST									
Rain	Temp	Rain	Wet			Normal			Dry		
		Temp	Hot	Normal	Cool	Hot	Normal	Cool	Hot	Normal	Cool
Wet	Hot		1							3	
	Normal			1	3	2	1	2			
	Cool				4	1	2	1			
Normal	Hot		3	2				2			1
	Normal								2	1	1
	Cool		1			1	2			2	2
Dry	Hot		2	1		1	1		2	1	1
	Normal		1	1	1		1	1	1	1	
	Cool					2				1	2

	Temperature, °F			Rain, inches		
	Hot	Normal	Cool	Wet	Normal	Dry
June	>70.0	67.2-70.0	≤67.1	>4.9	3.2-4.8	0.5-3.2
July	>74.2	72.2-74.2	<72.1	>3.8	2.7-3.8	0.4-2.6
August	>72.6	71.3-72.6	<71.3	>4.0	2.4-4.0	0.3-2.3

Table 24 b. Region 12 (Quincy) monthly weather relationships, 1901-1963.

JUNE		JULY								
Rain	Temp	Rain: Wet			Normal			Dry		
		Temp: Hot	Normal	Cool	Hot	Normal	Cool	Hot	Normal	Cool
Wet	Hot	1			1			1		
	Normal		1	1	1	3	2			
	Cool	1		2		1	2		2	2
Normal	Hot	1	1		2			2		
	Normal	1	1				1	1	2	
	Cool			3			3	2		1
Dry	Hot		1		3	1		4	3	
	Normal		4	2			1			
	Cool			1					1	

JULY		AUGUST								
Rain	Temp	Rain: Wet			Normal			Dry		
		Temp: Hot	Normal	Cool	Hot	Normal	Cool	Hot.	Normal	Cool
Wet	Hot					1		1	2	
	Normal	1	2		1	4				
	Cool			3		1			2	3
Normal	Hot		2		1	1			2	1
	Normal	1		1	2					1
	Cool			4	2	1		1		1
Dry	Hot	1			2	1	1	4		
	Normal	1	2	4	1	1				1
	Cool							1	1	

	Temperature, °F			Rain, inches		
	Hot	Normal	Cool	Wet	Normal	Dry
June	>76.5	72.5-76.4	572.4	>5.2	3.5-5.1	0.6-3.4
July	>80.5	77.8-80.4	≤77.7	>4.2	2.2-4.2	T-2.1
August	>78.7	76.5-78.6	≤76.4	>4.2	2.5-4.2	0.3-2.3

Table 24 c. Region 6 (Decatur) monthly weather relationships, 1901-1962.

JUNE		JULY									
Rain	Temp	Rain	Wet			Normal			Dry		
		Temp	Hot	Normal	Cool	Hot	Normal	Cool	Hot	Normal	Cool
Wet	Hot								4		
	Normal		1	1	2		2	1			
	Cool				2		2		1	1	4
Normal	Hot		1	1		2	1		1		
	Normal		1		1		1		1	1	2
	Cool		2	2	1		2				
Dry	Hot		1			3	2	1	2	2	
	Normal			1	3		1			1	
	Cool			1				2	1		

JULY		AUGUST									
Rain	Temp	Rain	Wet			Normal			Dry		
		Temp	Hot	Normal	Cool	Hot	Normal	Cool	Hot	Normal	Cool
Wet	Hot		1						4	1	
	Normal				1		1				3
	Cool			2	4	1		1	1	1	
Normal	Hot		1	1		1	1			1	
	Normal		1	2	3	1	1	1	1	1	
	Cool		1			1				2	
Dry	Hot		1	1		3		1	1	3	
	Normal				2		1	2			
	Cool						2	2	1	1	

	Temperature, °F			Rain, inches		
	Hot	Normal	Cool	Wet	Normal	Dry
June	>74.4	71.1-74.3	<71.1	>4.9	2.9-4.9	0.5-2.8
July	>78.0	76-78	<76.0	>4.0	2.3-4.0	0.1-2.2
August	>76.5	74.6-76.5	<74.6	>4.1	2.2-4.1	0.2-2.1

Table 24 d. Region 3 (Urbana) monthly weather relationships, 1889-1962.

JUNE		JULY								
Rain	Temp	Wet			Normal			Dry		
		Hot	Normal	Cool	Hot	Normal	Cool	Hot	Normal	Cool
Wet	Hot							6		
	Normal		2			2	2		2	
	Cool		1	2		2	2			4
Normal	Hot	5			2	1		2		
	Normal	2	1	2		3				1
	Cool			1	1	2		1		1
Dry	Hot				2	1		3	2	
	Normal			4		2	1	2		
	Cool		2	2		1	1		1	

JULY		AUGUST								
Rain	Temp	Wet			Normal			Dry		
		Hot	Normal	Cool	Hot	Normal	Cool	Hot	Normal	Cool
Wet	Hot	1			1	1		2	2	
	Normal			2					1	2
	Cool			6		3		2		2
Normal	Hot		1	1		1				
	Normal	2		1		3	2	1		
	Cool	3	1	1		2	3	1	2	
Dry	Hot		2	1	2	2		5		1
	Normal		1		1	2		1		
	Cool	1	1				1	1	2	

	Temperature, °F			Rain, Inches		
	Hot	Normal	Cool	Wet	Normal	Dry
June	>74.0	70.8-74.0	<70.8	>4.7	2.9-4.7	0.4-4.6
July	>76.3	74.3-76.3	<74.3	>3.9	2.4-3.9	0.2-2.3
August	≥74.5	72.3-74.4	<72.3	>4.0	2.6-4.0	0.2-2.6

Table 24 e. Region 11S (Mt. Vernon) monthly weather relationships, 1904- 1954.

JUNE		JULY								
Rain	Temp	Wet			Normal			Dry		
		Hot	Normal	Cool	Hot	Normal	Cool	Hot	Normal	Cool
Wet	Hot								2	
	Normal		1	3			2			
	Cool		3	2		2			1	1
Normal	Hot	1			3			1		
	Normal			1			2	2	1	
	Cool		1	2	1		1	1		
Dry	Hot				3	1		3	2	
	Normal		1	1			1		2	1
	Cool		1		1					

JULY		AUGUST								
Rain	Temp	Wet			Normal			Dry		
		Hot	Normal	Cool	Hot	Normal	Cool	Hot	Normal	Cool
Wet	Hot		1							1
	Normal		1			1	1	1	1	1
	Cool			2		1	2	2	1	1
Normal	Hot	3	2				x		1	
	Normal	1				3	1			
	Cool			3	1		1			
Dry	Hot	±			1	2		3	1	
	Normal			2			1	2	1	
	Cool		1		1			1		

	Temperature, °F			Rain, inches		
	Hot	Normal	Cool	Wet	Normal	Dry
June	≥76.2	73.0-76.1	<73.0	>5.2	3.4-5.2	<3.4
July	≥79.8	77.4-79.7	<77.4	>3.2	1.6-3.1	<1.6
August	≥77.7	76.1-77.6	<76.1	>5.0	2.4-5.0	<2.4

Table 25. Most likely rain amount in August following wet July-conditions in 5 crop-weather regions.

		Most likely August rain and its probability		
Region	Climatic Station	July wet-hot	July wet-normal	July wet-cool
10	Aurora	Dry (0.75)	Normal (0.56)	Wet (0.50)
3	Urbana	Dry (0.57)	Dry (0.60)	Wet (0.46)
6	Decatur	Dry (0.83)	Dry (0.60)	Wet (0.60)
12	Quincy	Dry (0.75)	Dry (0.63)	Wet (0.56)
11S	Mt. Vernon	Dry (0.50)	Dry (0.50)	Dry (0.50)

among all possible conditions shown, each probability value should be 0.33 (33%). Examination of the results and the probabilities indicate that when July was wet and hot, the probability of a dry August predominates at all stations, and is generally greater than the probabilities found for the other July rain-temperature combinations. In general, an inverse relationship exists at most stations for most combinations. That is, after a July with wet-hot or wet-normal temperatures, a dry August is most likely. However, persistence in rainfall is indicated when a wet-cool July has occurred, since a wet August is most likely at all locations except in Region 11S (southern Illinois). Chances of a wet August (except after a wet-cool July) are reasonably remote being 25% or less in all of the 5 regions. Further examination of the frequencies in Table 24 for both wet and dry conditions in the preceding months reveals that there is generally a marked tendency for a certain rain combination to follow given rain-temperature combinations in the preceding month, particularly when the prior month rainfall was extreme (wet or dry).

In conclusion, the results on monthly weather relationships between June-July and July-August indicate that when rain extremes occur in one month, chances of predicting the following month are much greater than expected from a random distribution. Thus, the results offer useful decision-making information regarding the choice of seeding model and seeding operations in Illinois. Certainly, the probabilities based on historical data and for the more extreme conditions in June or July suggest a basis for choice that is better than the present 30-day outlooks of the National Weather Service, and would be better to use than a random decision. These results are sufficiently encouraging to suggest further research of the conditional relationships.

SUMMARY AND CONCLUSIONS

Research was carried out to provide quantitative estimates of the potential effects of cloud seeding on the two major Illinois crops, corn and soybeans. The three basic phases of this research included: 1) determination of weather-

-yield relationships for the two crops with division of the state into regions of equivalent yield characteristics; 2) development of methods to evaluate quantitatively the effect of seeding-induced rainfall changes on crop yields; and 3) preliminary assessment of yield changes resulting from cloud seeding and their economic implications. A primary consideration in the development of the methodology for assessing seeding-induced benefits or disbenefits in Illinois was to establish methods applicable to all areas of the United States.

In the Illinois study, the state was divided into 13 regions, based on county yield-weather-statistics, and a regression equation derived for each crop in each region by relating crop yield to technology indices and various parameters of temperature and precipitation. The regressions were based upon use of crop yield and climatological data for the period, 1931-1968. Through use of the appropriate equation, hypothetical seeding models were then applied to actual weather data in the sampling period to obtain estimates of yield increases or decreases resulting from augmentation of summer rainfall. Two types of hypothetical seeding models were used. One investigated the effects of various constant percentage increases applied to the naturally-occurring July-August rainfall. The other type, probably more realistic, assumed that seeding efficiency decreases with increasing daily rainfall amounts. Sufficient models were tested to cover the expected range of seeding capability in the foreseeable future.

From the hypothetical seeding, frequency distributions of yield changes were developed for each specific model, each crop, and each region. The yield-change distributions for the two crops were then pooled to obtain an economic frequency distribution of seeding benefits for each region, based upon 1968 technology levels and current corn and soybean prices. Frequency distributions were developed for potential seeding operations lasting 1, 2, 3, and 5 consecutive years.

In addition to the above primary studies, a number of supplementary studies were made to assit in evaluating potential benefits of seeding, and the more important of these are summarized in this report. Also, attention was given to analysis of seeding costs, the climatology of July-August dry periods, and the prediction of July-August rainfall through use of conditional probabilities.

In general, analytical results indicated that in most regions of Illinois corn and soybean crops would be benefited economically in the majority of the growing seasons through a cloud seeding program, provided that the seeding operator had the capability to produce rainfall increases of 10% or more. However, results of this study also show that the operator must be able to define accurately the rainfall output from his seeding treatment or more damage than benefit could result from his activities.

However, assuming the seeding operator has the capability to define and control his seeding operations satisfactorily, the Illinois studies indicate that strictly from the standpoint of probability of economic benefit or disbenefit, it would usually be advantageous to initiate cloud seeding whenever a "dry spot" develops in the state. It was found that the hypothetical rain-increase models are helpful the majority of the time in most regions of the state when the seeding-induced yield changes for the two crops (corn and soybeans) are pooled economically.

Although the economic pooling usually produced favorable net results, other analyses indicate that differential effects may occur from seeding corn and soybean crops in a given region during a significant percentage of the years. That is, one crop may have its yield increased while the yield of the other crop is decreased. However, these differential effects were found to occur most frequently in years in which yield increases and decreases were relatively small. Nevertheless, this finding stresses a problem which must not be overlooked in evaluating potential seeding benefits. It is a potential situation which can lead to major disagreement over the results of a seeding program in a specific area.

Over the 38-year sampling period, reaction to potential seeding was found to vary substantially between regions in Illinois when the same seeding model was employed. This regional variation results primarily from differences in soil properties between regions, and, to a lesser extent, to differences in growing-season climate. Thus, a seeding model can have different degrees of effectiveness between regions, and results in one region are not necessarily transferable to another.

Furthermore, as shown by the frequency distributions of rainfall changes associated with the several variable-change models, seeding effectiveness may vary considerably from year-to-year in a given region with the same seeding model. This results from the temporal variability in the natural distribution characteristics of storm and daily rainfall (intensity and volume) which, in turn, affect the seeding-induced rainfall output. This temporal variability complicates the problem of statistical verification of seeding results and helps explain some of the controversial results obtained in past cloud seeding experiments and commercial operations.

From a percentage standpoint, the statewide average yield change resulting from seeding was found to be very similar for both crops with the various hypothetical seeding models employed in the study. However, average yield change in bu/acre was greater with corn which has a much higher acreage yield than soybeans. Also, comparisons indicated that the year-to-year variability in seeding effect was greater with corn than with beans.

The importance of maximizing the rainfall augmentation from seeding was brought out in analyses which assumed gradual increase in seeding capability from a seeding model producing near zero augmentation (Model C) to models producing average July-August rainfall increases of 12%, 25%, and 40%, (Models B, A, and E). With these progressive increases in seeding effectiveness, the state average of added income per seeded acre increased progressively by amounts of $1.98, $2.15 and $1.98, or a total increase of over $6/seeded acre from Model C to Model E.

A study of the di matology of July-August dry periods in Illinois led to the conclusion that there is not a substantial deficiency in the number of days with rain during these periods, but rather a distinct lack of moderate to heavy rainfall days. Thus, seeding operations should be successful through enhancement of existing rainstorms, rather than attempting to produce rain on days with no naturally-occurring precipitation. This study also showed that summer dry areas are small in areal extent, averaging about the size of an Illinois county. A distinct tendency was noted for dry periods to develop and occur repeatedly during a period of 7 to 14 years, and then essentially to disappear for 5 to 15 years. Also, great temporal variations in dry areas were noted within the state, and this suggests that mesoscale conditions not presently understood lead to development of such areas.

A limited study was made of the use of conditional probabilities as a guide in scheduling seeding operations in July and August. Results indicated these can provide useful decision-making information that is superior to the present 30-day outlooks of the National Weather Service.

RECOMMENDATIONS

In preparation for future weather modification activities, the techniques and methods developed in the Illinois research should be used to accomplish similar studies in other regions of the United States, where the major crops are different and where climatic conditions are substantially different.

The general methodology developed in the Illinois agricultural studies should be applied to the evaluation of potential benefits of weather modification on water supplied that are obtained from surface waters and shallow groundwater acquifers. As in the case of the crop-weather study, the method will yield useful first approximations at a minimum research cost.

Whenever studies of the potential benefits of weather modification are evaluated for a region, climatic studies of the frequency distribution of dry periods in the study region should always be an integral part of the investigation.

Results of the Illinois study show that further attention should be given to the use of conditional weather probabilities as a statistical forecasting tool to facilitate and improve the efficiency of cloud seeding operations in the future.

Relationships, such as developed in the Illinois research, should be considered preliminary, and they should be refined as more precise information and knowledge on seeding capabilities become available in the future.

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